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Edited for the Council by J. LAURENCE PRITCHARD, Fellow

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NOTICES

Donations

The Council desire to acknowledge gratefully the gift of Journals from Miss L. Chitty and Mr. F. W. Hills.

The Guggenheim Fund for the Promotion of Aeronautics

The Council have received a letter from the Daniel Guggenheim Fund for the Promotion of Aeronautics. The letter, which is signed by Mr. Harry F. Guggenheim, the President of the Fund, says, *inter alia*:—

> " It affords me great pleasure to advise you that the Daniel Guggenheim Fund for the Promotion of Aeronautics has approved a grant of $5,000 to the Royal Aeronautical Society.
>
> " This grant will be available after January 1st, 1927. It is the hope of the Fund that this grant may stimulate the growth and strength of the Society to such a point that within a short while financial assistance from without will be unnecessary."

The Council have cabled their grateful thanks to the Trustees of the Fund for their generous gift.

Lantern Slides

Members are reminded that the Society possesses a comprehensive collection of lantern slides, which may be borrowed for lecture purposes.

Library

The following books have been received and placed in the Library:—" The Technical Report of the Aeronautical Research Committee for 1924-5," Vol. I.; " Aeroplanes: Model and Full-Scale," Vol. II.; " Airscrews, Engines, Materials, etc."; " Aerial Surveying by Rapid Methods," by B. M. Jones and J. C. Griffiths; " The Elements of Aerofoil and Airscrew Theory," by H. G. Glauert; N.A.C.A. Reports, Nos. 226, 229, 233, 234, 236, 238 and 245; N.A.C.A. Technical Notes Nos. 235 to 241; a set of Reports on the Progress of Work in the Civil Aviation Department of the Air Ministry from May, 1919 to March 31st, 1926; Proceedings, Vol. I., 1926, of the Institution of Mechanical Engineers; Reports and Memoranda of the Aeronautical Research Committee, Nos. 1004, 1008, 1011, 1012, 1013, 1021, 1022, 1024, 1025 and 1026; and the Airworthiness Handbook for Civil Aircraft, A.P. 1208.

Chairman

Colonel the Master of Sempill, A.F.C., Associate Fellow, assumed office as Chairman of the Society for the year 1926-1927 on October 1st.

Forthcoming Arrangements

Tuesday, October 5th, 5.30 p.m.—Council Meeting.

Thursday, October 7th, **8.30 p.m.**—Colonel the Master of Sempill, A.F.C., A.F.R.Ae.S.: "Aero Engine Fuels of To-Day and To-Morrow."

Thursday, October 21st, **6.30 p.m.**—Mr. W. R. D. Jones, M.Sc.: "Notes on Magnesium and Some of Its Alloys."

Thursday, November 4th, **7.0 p.m.**—Joint Meeting with the Institution of Automobile Engineers. Mr. G. F. Mucklow: "Hydrogen as an Auxiliary Fuel for a Solid Injection Engine."

All the lectures will take place in the Theatre of the Royal Society of Arts, 18, John Street, Adelphi, W.C.2 Particular attention is drawn to the times at which the lectures are held.

Alteration to Programme

The lecture announced for Thursday, November 25th, has been cancelled. Major Buchanan's paper on "The Two-Seater Light Aeroplane Competition, 1926," will be published in the Journal.

Coventry Branch

The following programme has been provisionally arranged:—

September 28th.—Captain F. L. Barnard: "Commercial Aviation."

October 21st.—Major F. M. Green, Fellow: "The History of the Aeroplane."

November.—Prof. B. Melvill Jones, A.F.C., Associate Fellow, on some subject to be announced later.

December.—Mr. C. Handley Page, C.B.E., Fellow: "The Control and Stability of Aircraft."

J. LAWRENCE PRITCHARD,
Honorary Secretary.

PROCEEDINGS

EIGHTH MEETING, SECOND HALF, 61ST SESSION

The Eighth Meeting of the Sixty-First Session of the Royal Aeronautical Society was held in the Society's Library, at 7, Albemarle Street, London, W.1, on Thursday, April 29th, 1926, when a paper reviewing the present position of Airship Research and Experiment was read by Colonel V. C. Richmond, Associate Fellow.

Air Vice-Marshal Sir W. S. BRANCKER said: Colonel Richmond needs no introduction from me. He will in his lecture tell you of the great and valuable research and design work which has been made in his department, and I hope that his exceedingly well-informed paper will be followed by a sound discussion.

A REVIEW OF THE PRESENT POSITION WITH REGARD TO AIRSHIP RESEARCH AND EXPERIMENT

BY LIEUT.-COL. V. C. RICHMOND, O.B.E., B.SC., A.R.C.S., A.F.R.AE.S.

(1) *Introductory*

Prior to the war, experience in this country in the production of successful rigid airships may be counted to be practically negligible. The war period, however, produced an intensive programme of rigid airship building in which the early designers were seriously handicapped owing to this lack of previous experience, and owing to the insufficient time and opportunities for research and experiment, a state of affairs which persisted to the end of the war.

The first rigid airships in this country were built with very little knowledge of the experience which had been gained in Germany. When, however, the hulls of some of the German Zeppelin airships were captured, an immense amount of valuable information came into our possession which enabled us to build airships which were a considerable improvement on the earlier ones. Since that time the rigid airships which have been built in this country and in America have followed almost completely the lines of design developed by the Zeppelin Co.

The fact that designs of successful airships which could be copied came into our possession in this way had one unfortunate effect, in that it masked the necessity for a programme of consistent research and experiment in order to establish a sound basis for our knowledge in this country.

For reasons which need not be entered into in detail here, but which, personally, I consider practically undebatable, we are now constructing in this country airships which are practically twice as large as anything which has been constructed in Germany. One very potent reason at any rate for adopting this great increase in size is the improvement in design which should be rendered possible thereby. Personally, I have the greatest admiration for the ingenuity displayed by the Zeppelin designers and for the success which they have achieved. Whether the research and experiment which they have carried out has been of such a complete and comprehensive nature as to enable them to confidently jump from a design of an airship such as the Los Angeles of $2\frac{1}{2}$ million cubic ft.

to one of 5 million cubic ft., I do not know. Whether their experience is entirely of the empirical kind which would necessitate their adhering very closely to their present lines of design in making such a jump, I also do not know; but my object in these speculations is to point out how essential it is in this country for us to make good the war-time deficiency by consistent and continuous research. Speaking with all diffidence, I will say that only in this manner shall we discover how far, if at all, it is possible to improve on German design by knowledge of a fundamental rather than of an empirical character.

A comparatively small share of aeronautical effort has been devoted to the airship in the past, as compared with the aeroplane. This is no doubt largely attributable to the relative size of individual craft of the two classes, which greatly affects the relative cost of each step in development, although having no direct bearing on the cost of operation of serviceable craft.

The aeroplane promising so much has provided since its advent an almost sufficient scope for all available talent. It is probably fair to say in consequence that the airship has not hitherto realised expectations based upon current engineering knowledge to the same degree as craft heavier-than-air. During, however, the period of enforced idleness which occurred after the war, and since that time, the airship has attracted wider attention amongst aeronautical engineers and experts of all kinds, with the result that a better appreciation of the problems involved has been gained and valuable additions to our knowledge have been made in this respect, both in this country and in America.

We are still, however, in the middle of our present programme, and it is not yet possible to see the full results of all the work which is in hand, or indeed to appreciate its full significance. It is for this reason that the title of this paper has been altered from that which was originally published by the Society.

It was felt that the most useful thing at this stage would be to review the present position with regard to theoretical model and full scale work under the two broad headings of the study of the external forces which act upon an airship and on the internal distribution of stresses in the structure arising from these forces.

(2) *The External Forces Acting Upon an Airship*

It will of course be readily appreciated that the loading of an airship structure arises from a combination of static and dynamic causes which vary with the amount of dead weight or buoyancy which the ship is carrying and with the speed and type of manœuvre which is being executed.

So long as the ship is relatively small and the speed is low, the static forces predominate and the aerodynamic forces are negligible in comparison. The determination of the static loading needs no comment, being a simple matter except perhaps in regard to the transmission of the lift of the gasbags to the structure. Here, water models can be of considerable assistance, and incidentally there is plenty of scope for ingenuity in devising a practical form of net which effectively transmits the gas pressure forces to the joints of the structure in a manner which is mathematically determinable.

Very large forces may arise from internal gas or air pressure when the airship rapidly changes altitude if these pressures are not properly controlled. The study of vertical air currents likely to cause rapid change of height has been receiving considerable attention. The matter has been thrown into greater prominence by the experience of the fatal accident to the American airship Shenandoah. There appears to be little doubt that vertical velocities of as much as 4,000ft. per minute may be met with in the heart of a severe thunderstorm. An examination of the automatic valve capacity of the German airships and their British counterparts indicates that excessive pressures would be generated if the rate of rise exceeded much above 1,000ft. per minute.

With an efficient meteorological service issuing systematic warnings and a careful analysis of the frequency of storms in different parts of the world, it should be possible to reduce almost to zero the risk of running into such severe currents as 4,000ft. per min. Steps have been taken to put such a service into being, but even so it is thought desirable to provide sufficient valve capacity to deal with the 4,000ft. per min. I have mentioned. This increased rate of discharge coupled with the greatly increased size of the gasbags as compared with previous airships has called for special design and experiment, on the type of arrangement of valves, to meet it, but no great difficulty is foreseen in this direction.

The fact that aerodynamic forces assume prime importance with increase in size and speed was tragically emphasised by the disaster to the R.38. The fact that designers did not understand and provide for the forces imposed upon an airship when riding to a mooring mast has been commented on by Major Scott in his lecture to this Society, and is emphasised by the accidents which occurred to the R.33 and the Shenandoah whilst moored to their masts. As a consequence of all this, however, there has grown up since the war a much clearer insight into what are the critical loading conditions for an airship, and with the material available in 1924 the Airworthiness of Airships Panel [1] endeavoured to lay down a schedule of these conditions with appropriate factors of safety to be applied to each. With the experience which is now being gained in the mathematical investigation of an entirely new design, it will be possible in due course to amplify the report of the Panel and to indicate the manner in which the various recommendations should be interpreted. Some 300 cases of primary loading or combinations of loading have been worked out for R.101. They are very illuminating in the light they have thrown on the relative severity in the different parts of the ship of the various possible conditions of flight, and in the appropriateness or otherwise of the factors of safety suggested by the Panel.

The results may be briefly summarised in the following table, which indicates the relative severity with regard to shearing forces and bending moments of the different conditions of flight. Positions near the nose, in the centre of the ship and near the tail just in front of the fins, have been chosen. With regard to these positions, however, it must be realised that this table may not be too generally applied, as the position of any large concentrated weight such as the passenger car will have a marked influence on the relative severity of the different flight conditions in different parts of the ship. In columns 2 and 4 is shown the order of severity which arises when the factors suggested by the Airworthiness Panel are applied.

Position.	Shearing Force.		Bending Moment.	
	(1) Without factor.	(2) With factor.	(3) Without factor.	(4) With factor.
Nose	Mast Case	Mast Case	Mast	Mast
	Turning	Static	Turning	Static
	Static	Turning	Static	Pitched
	Pitched	Pitched	Pitched	Turning
Centre	Pitched	Pitched	Pitched	Pitched
	Turning	Static	Turning	Turning
	Mast Case	Mast	Mast Case	Static
	Static	Turning	Static	Mast
Tail	Pitched	Turning	Turning	Pitched
	Turning	Pitched	Pitched	Turning
	Mast	Static	Mast	Static
	Static	Mast	Static	Mast

It has been stated above that the chief problem in the assessment of the

[1] R. & M. 970.

external loading is a proper appreciation of the aerodynamic forces. It would perhaps be well, therefore, at this point to give some more detailed account of the research and experiment which is being carried out in this direction.

(2A) *Theoretical Work*

The valuable summary given by Mr. R. Jones in his R.38 Memorial Prize paper [2] shows that important theories have been developed in this country during the past four or five years whereby with the aid of constants obtained from model experiments the designer can deduce practically all the information he requires with regard to the characteristics of an airship in steady motion. It is outside the scope of this paper to treat any of these matters in detail here, especially as the paper deals with them in such admirable detail.

There is, however, one section of the work which calls for special comment in view of the alterations which are taking place with regard to ideas on the shape of airship hulls. Before dealing with this, however, let me say that I consider that any attempt to treat the aerodynamics of airships more empirically and less fundamentally than has been done in the theories referred to above will certainly lead to erroneous results if a drastic alteration in shape is contemplated.

It is possible to estimate the pressure distribution and lateral force distribution on a true spheroid in pitched or circling flight by the methods of pure hydrodynamics. The results of comparison of theoretical work with experiments on a spheroid in a wind tunnel and on a whirling arm are referred to later.

Model measurements of total lateral force and moment must form the basis of all diagrams of aerodynamic loading. Unfortunately, the pressure plotting results obtained on a model never integrate up to give the correct value of lateral force and moment, owing presumably to skin friction effects. A certain portion of the nose of most airships approximates very closely to a spheroid. Theoretical deductions from the spheroid may be applied to this portion of the airship. The remainder of the lateral force and pressure distribution curves may be filled in by trial and error so as to give the correct value of total lateral force and moment as measured on the model. This avoids the difficulties explained above in connection with using pressure plotting results from a model; it is very convenient for stressing work, and cannot be greatly in error for this purpose.

In an airship like R.33, which has a long parallel body, only a small portion of the hull near the nose is truly ellipsoidal and the application of the above method is very speculative. It will be seen from the airships Bodensee, Nordstern, Los Angeles and R.80 that the modern tendency is to make the shape of rigid airships shorter, fatter, and more perfect. This has been pushed still further in the R.101. More will be said about the effect of this later, but meanwhile it may be noted that it approximates very closely to an ellipsoid for practically half its length, and it has been found possible to apply the theoretical method mentioned above very successfully. The pressure distribution curves so obtained do not seriously differ from corresponding curves of pressure measured on the model, but the difference is sufficient to give, when integrated, the correct values of total lateral force and moment in the former case, and incorrect values in the latter case.

Many attempts have been made in the past to find a formula for a mathematical airship shape which will be ideal from an aerodynamic point of view. These have not met with much success. Certain guiding principles have been discovered experimentally, however, which can probably be met quite well by joining up a number of different curves to form the complete shape. In the case of R.101, owing to the type of construction which is being employed, it

[2] "The Aerodynamical Characteristics of the Airship as Deduced from Experiments on Models with Applications to Motions in a Horizontal Plane." R. Jones, *Jour. Roy. Aero. Soc.*, February, 1924.

was thought desirable to have a mathematical formula to represent the complete shape so that the geometry could be calculated as accurately as possible. A useful method was evolved in which an ellipse was taken and distorted to give an airship shape by multiplying its ordinates by those of another curve such as a straight line, a second ellipse or a parabola, etc. In this way it was found possible to evolve a number of shapes, one of which fulfilled all the requirements of a bluff nose, a pointed tail not too fine, and a continuously and regularly decreasing curvature from nose to tail. It gave a very low resistance coefficient when tested in the wind tunnel.

There still remains, of course, the vexed aerodynamic problem of what happens to an airship in unsteady air conditions such as gusts. Model work on this is practically an impossibility. Probably the only hope of dealing with the problem experimentally is to actually measure the strains which occur in the components of the airship when flying through disturbed air. This will be further discussed later.

Several theoretical methods have been evolved for estimating the forces acting on an airship in a vertical gust.[3] They all suffer from two serious defects, however. In the first place they are founded on totally insufficient knowledge as to the probable area of the gust, the composition of the wind velocities and accelerations within it, and at the boundary. Secondly, it is assumed that when instantaneous values of pitch and relative air velocity have been found, the pressure distribution and hence the aerodynamic force on the airship will be the same as that which exists in ordinary rectilinear flight for the same pitch and velocity. In reality there is probably a very different pressure distribution which cannot be imitated in a wind channel.

The problem of variable winds is particularly important in connection with the influence they may have on an airship when moored to a mast. If the variations are of a simple character, it is possible to deal with them by the means which I have indicated in the Appendix to this paper. The method suffers, of course, from the defects referred to above, but Major Scott [4] has already explained to this Society the steps which are being taken to cope with the meteorological aspect of the problem. Probably the most useful purpose which the method can serve is to enable the experience gained from the breaking of the nose of R.33 to be applied to the determination of the forces which would act on a different airship under the same conditions. The method of doing this has already been sufficiently indicated by Major Scott and therefore needs no further explanation here.

(2B) *Model Work*

Wind channel experiments on airship models in this country during the war period were directed mainly towards the examination of some of the properties of a specific design of ship. There was little or no time for consistent fundamental research as, for example, into the characteristics of a carefully-graded series of shapes of varying fineness ratio combined with a graded series of fins. From such isolated and disconnected experiments as have been performed, however, there has grown up a better understanding of the desirable aerodynamic characteristics for an airship and a better appreciation of the compromise which it is possible to strike between these. At one time attention was directed almost exclusively to obtaining low hull drag and the necessary control and stability in flight. The bare hull represents only about 50 per cent. of the total drag, and although considerable advance has been made in devising shapes of low drag, there is obviously much to be gained by paying close attention to all those

[3] See for instance, "Forces on Airships in Gusts," C. P. Burgess, Nat. Av. Comm. for Aeronautics. Report No. 204.

[4] "The Development of Airship Mooring," G. H. Scott, *Jour. Roy. Aero. Soc.*, 1926.

external items which represent the other 50 per cent. Again, the all-important development of mast mooring has shown the need for careful attention to the control and stability characteristics of the airship when being hauled to or when riding to a mast. Yet again the lift-drag ratio of various airship shapes when pitched is a matter which would pay for closer study than hitherto, since any improvement in this respect would ease the problem of flying under those meteorological conditions which cause large fluctuations in the lift of the gas. This may also be important in connection with the problem of aeroplane carrying on airships.

For all these reasons it is earnestly hoped that when pressure of work in connection with the present design is eased and before some new design comes forward for specific examination, opportunity will occur for carrying out fundamental wind channel research of the nature I have indicated.

There has been sufficient time, however, with the design of R.101 to make a more complete series of model experiments than on any previous British airship, and in some instances to examine the effect of certain variations. It would be most valuable if a parallel and equally complete set of experiments could be carried out on the full-sized ship, and it is hoped that ample opportunity for this will occur.

The low fineness ratio employed in modern airships has already been commented on. As early as 1919 the National Physical Laboratory tested a shape, U.721,[5] which had a fineness ratio of 4.62 and which was found to have a very low resistance coefficient. This coefficient was .0069 as compared with .0113 for the R.33 shape, and this represents only about 2½ per cent. of the resistance of a flat plate of the equivalent cross-sectional area. This shape has formed the basis for the design of the shape of the new airship, which has therefore a correspondingly low drag coefficient. Experiments have shown further that when a fin of a carefully-chosen profile is combined with the new hull shape, the fin efficiency is considerably higher than that obtained with the Zeppelin-shaped fins on the longer and thinner hulls. It is possible that some aerodynamic advantage would be gained from ships still shorter and fatter than those contemplated at present, but it must be remembered that the very large diameters which result give rise to their own special structural and housing difficulties.

Pressure plotting experiments have been carried out on the surface of a true spheroid in a wind tunnel.[6] These experiments show the good agreement between experiment and the results obtained by the methods of pure hydrodynamics over the front half of the spheroid, but the agreement begins to fall away over the back half. Similar experiments have also been carried out on the whirling arm. It is hoped that a report on these by Dr. R. Jones will shortly be published, but meantime this report may be anticipated to the extent of saying that the results obtained are of an exactly similar character to those obtained for rectilinear motion in the wind channel.

As far as pressure plotting experiments on the model of R.101 go, it is interesting to compare the values of drag, lateral force, and moment obtained by integrating these pressures with the similar quantities measured on the balance in the wind tunnel. The results are summarised in the following table:

	Integrated drag.	Integrated Lat. Force.	Integrated moment.
Yaw	Drag measured on balance.	Lat. force measured on balance.	Moment measured on balance.
0	39·5%	—	—
5	59%	71%	92%
10	—	99%	99%
15	71%	104%	97%
20	—	110%	97%

[5] *Vide* R. & M. 607.

[6] R. & M. 600.

No experiments with an R.101 model have as yet been carried out on the whirling arm as the new shape was found to lend itself readily to the theoretical treatment mentioned earlier for lateral force distribution in circling flight. In the case of R.33, however, the application of the theoretical method is much more speculative as has been already explained and it may prove desirable to put such whirling arm experiments in hand in order to form a basis of comparison with the full-scale results which have been obtained with pressure plotting on this ship.

The failure of airship fins in flight is by no means an unknown occurrence. There have been the cases of the R.32 and R.36 in this country and of the Roma and Shenandoah (at the mooring mast) in America. This point is receiving special attention. Thus the model fins of R.101 have been pressure plotted in the wind channel, and the full-scale fins of R.33 have been pressure plotted in flight, but knowledge of the scale-effect on fins (if any) is still wanting and could probably be most rapidly gained by pressure plotting the R.33 fins on model scale.

(2c) *Full-Scale Work*

The principal items to record here are the full-scale experiments carried out with R.33 in October last year. It is only possible within the scope of this paper to give a very brief description of these experiments, but a full account will be published later. Originally the ship was prepared for the experiments in April 1925, but she broke away from the Pulham mast on April 16th, and a new nose had to be designed and built before she could be got into the air again. The experiments were undertaken at the suggestion of the Aeronautical Research Committee and an outline programme was prepared by Professor L. Bairstow. Although it was possible to institute more searching investigations than had been carried out in the past with the pressure distribution on models, it was considered that there was insufficient experience with regard to the degree of accuracy with which such model results could be applied to the full-sized airship.

A study of Mr. Frazer's excellent paper [7] will show how great had been the difficulties associated with the organisation of such full scale experiments in the past. A very large number of holes not too widely spaced, and a large number of duplicate observations are required in order to disentangle the effects of local irregularities, and unsteady conditions, to give a really useful mean curve. For this reason 200 holes were concentrated on one approximately horizontal generator of the hull and 100 holes on the upper fin in preference to spreading this number of holes over the whole surface of the hull and fins. Previous experiments had shown the necessity for paying most careful attention to the design of the pressure orifice if consistent results were to be obtained. For this reason the tubular orifices were fitted flush into the face of a continuous metal band 6in. wide. Twelve R.A.E. type photomanometers [8] were mounted in the keel of the ship. The lamps of the manometers were connected in series to a battery, switch, and tell-tale, in the control car, so that the whole of them could be exposed simultaneously. Four flying pitot and static heads were suspended 50ft. below the bottom of the hull, the static tubes being connected to one main in the keel and the dynamic tubes to a second main. Each manometer had the necessary number of connections to these mains to allow the correction for tilt to be made and a record of $\frac{1}{2}\rho V^2$ to be taken.

The experiments required a considerable number of observers. Owing to the difficulty and expense in keeping these observers on the station waiting for

[7] "The Rigid Airship in Relation to Full-Scale Experiment," R. A. Frazer, *Jour. Roy. Aero. Soc.*, September, 1925.

[8] *Vide* R. & M. 895.

the very favourable steady weather conditions required, it was decided to extend the duration of the first flight sufficiently to enable a large number of observations to be taken and the whole procedure was carefully rehearsed in the keel of the ship prior to flight. For the same reason, arrangements were made for the recharging of the instruments and the development of the records during flight in a dark room provided in the keel of the ship. The whole pressure system comprised some 22,000ft. of tubing. All tubes were carefully tested and cleared just before flight. Owing to it proving possible to carry through the complete programme in one flight under ideal weather conditions at night, no leaks developed in the system and only four out of the 300 tubes became blocked by moisture. Every exposure of each particular manœuvre was repeated; 42 exposures in all were made covering straight, pitched, and circling flight at different speeds and with various rudder and elevator angles. The somewhat arduous task of reducing the observations of 300 holes for each of the 42 exposures has just been completed, and it is possible to make some brief reference to the results. Some mean curves produced from a number of observations are given in Figs. 1, 2, 3 and 4, where they are compared with the corresponding model observations. In general the shape of the full scale curves agrees very well with the shape of the model curves. There is a decided kink at the nose, due no doubt to the fact that aft of Fig. 3 the carefully-shaped curved girders in the nose change suddenly to a series of straight longitudinals from frame to frame. There is a tendency to *local* instability in the tail just aft of the centre line power car, but the general shape of the curve remains good.

The most noticeable difference between the model and the full scale curves is the tendency of the latter to lie above the former. There is a variety of possible explanations for this, it being important to remember that it is extremely difficult to define the precise attitude of the ship, the pitch and yaw at the moment of exposure. The possible causes of this shift may be briefly summarised as follows :—

1. Influence of unrecorded pitch.
2. A slight yaw due to change of wind or failure of the coxswain to maintain direction.
3. Lack of symmetry in the airship which may be either permanent or else temporary owing to change of shape of the hull permitted by slackness in the shear wires.
4. Varying bulge in the outer cover.
5. Error due to lag in pipes.
6. Error in static pressure readings due to the system being saturated with alcohol vapour from the manometers.

It is possible to obtain some quantitative evidence on all these points except 1 and 4. Although this tends to reduce the discrepancy, there appears to be still something left to be explained by scale effect. If the shift to be explained in this way is an equal shift up in all generators or an equal shift towards the axis on all generators, the aerodynamic shears and bending moments as estimated from the model will still be correct. A slight difference in the shift on different generators would exert an almost negligible influence on the bending moments and shearing forces on the hull. It has been explained earlier that there are no model pressure plotting results for comparison purposes in circling flight or on the fins. The full scale results on the fins, however, were uniformly good and consistent, and may be illustrated by the examples shown in Figs. 5 and 6. It is well known that in circling flight the yaw on an airship is zero near the nose and a maximum at the tail. For this reason, although the force on the fin is always of the same sign, the force on the rudder may change sign as the rudder angle is increased. This will be clearly seen by comparison of the two figures.

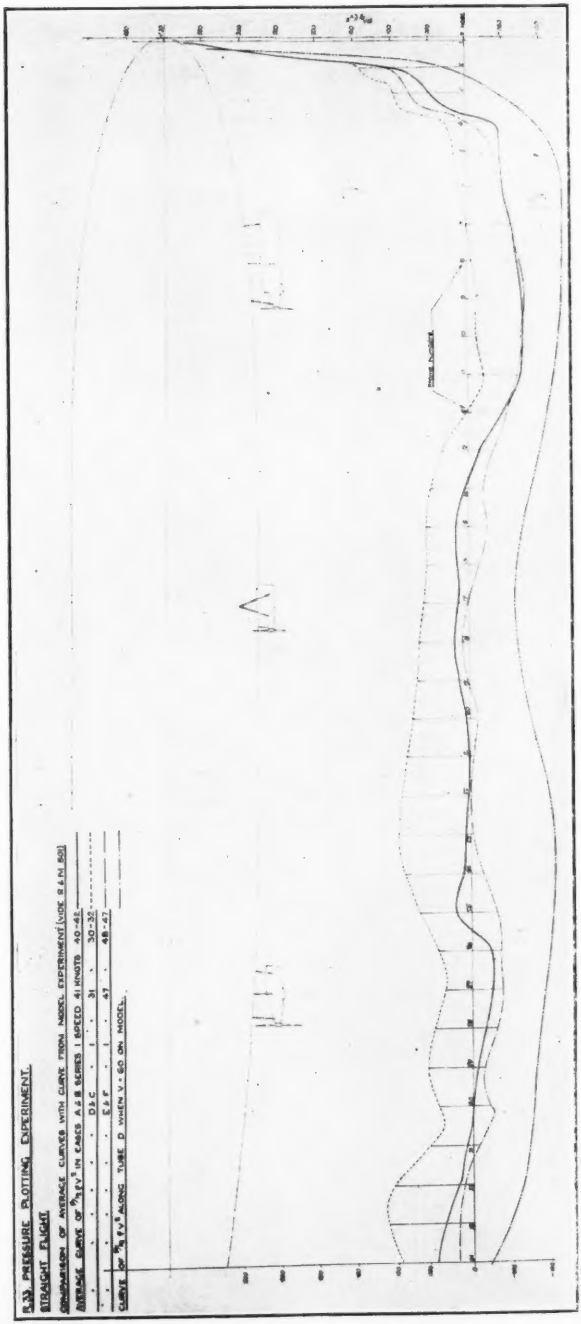
R.33 PRESSURE PLOTTING EXPERIMENT.
STRAIGHT FLIGHT.
COMPARISON OF AVERAGE CURVES WITH CURVE FROM MODEL EXPERIMENT (VIDE R & M. 501)
AVERAGE CURVE OF $P_s/\frac{1}{2}\rho V^2$ IN CASES A & B SERIES I SPEED 41 KNOTS 40-42
" " " " " D & C " " 31 " 30-35
" " " " " E & F " " 47 " 48-42
CURVE OF $P_s/\frac{1}{2}\rho V^2$ ALONG TUBE D WHEN V = 60 ON MODEL.
TRUE ANGLE

FIG. 1.

Pressure plotting curves—straight flight.

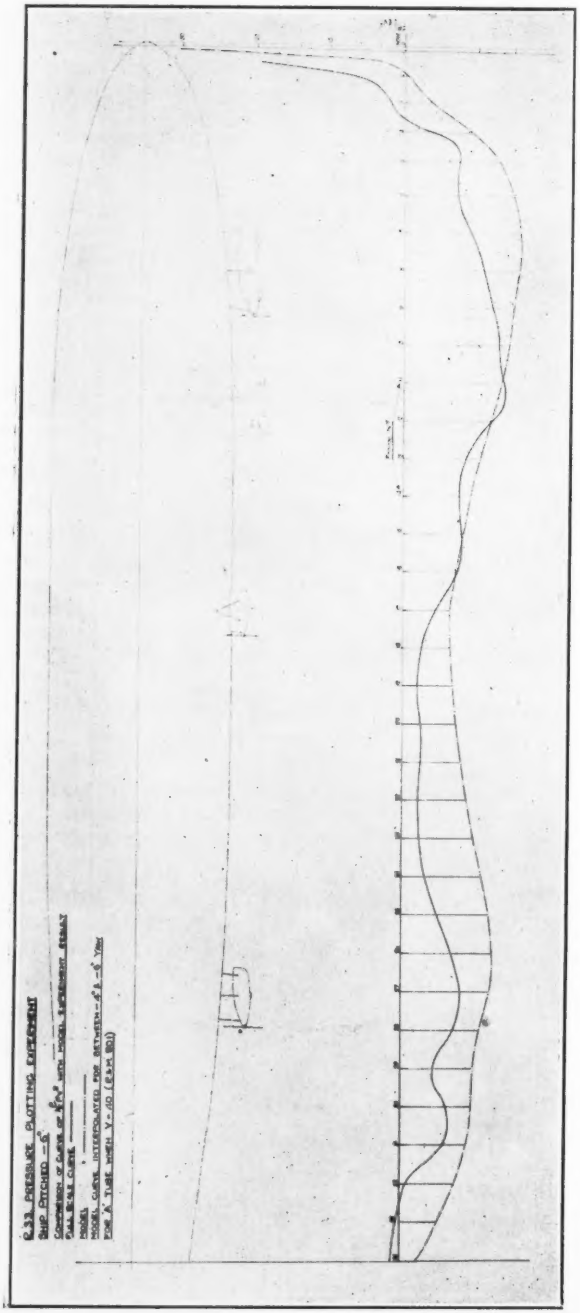
R.33. PRESSURE PLOTTING DIAGRAM
SHIP PITCHED — 5°
CONDITION OF GAS AT
GAS SCALE CURVE
MODEL
MODEL CURVE INTERPOLATED FOR
FOR A TRUE WIND V = 60 (R.A.S. KTS)

FIG. 2.

Pressure plotting curves—pitched flight 5°.

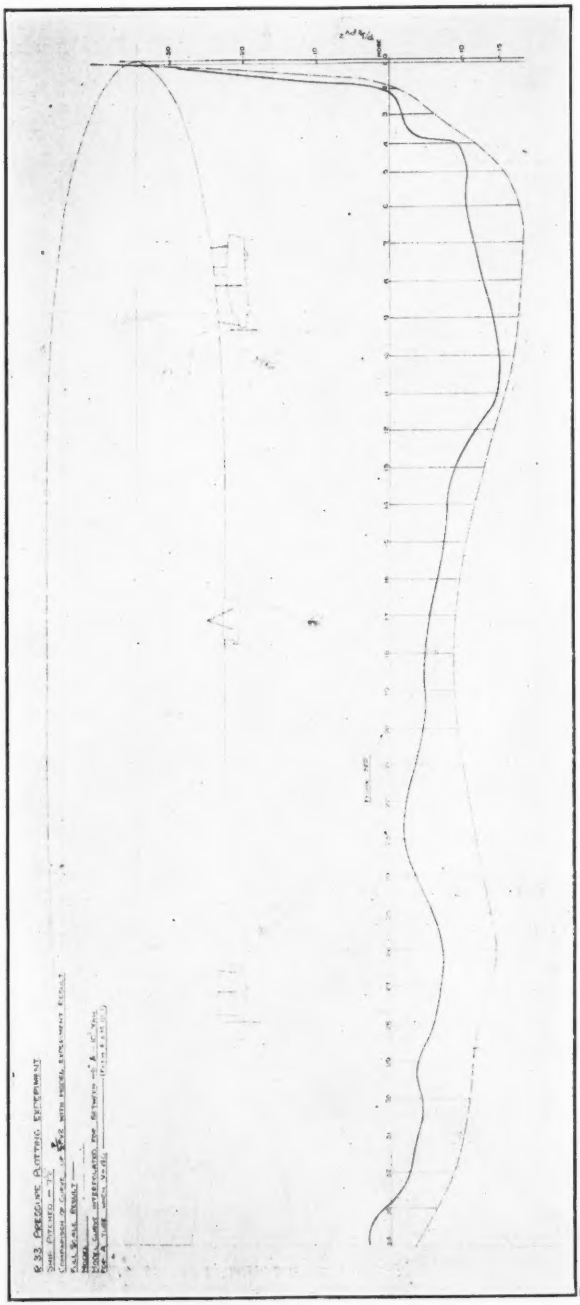

FIG. 3.

Pressure plotting curves—pitched flight 7½°.

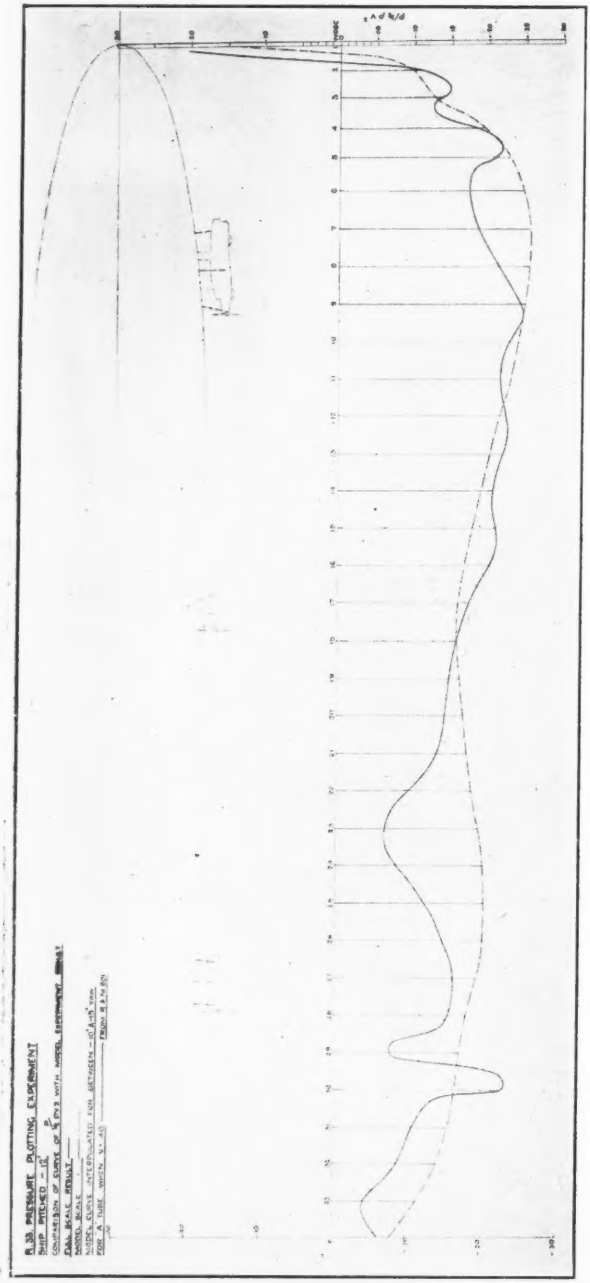

FIG. 4.

Pressure plotting curves—pitched flight 12°.

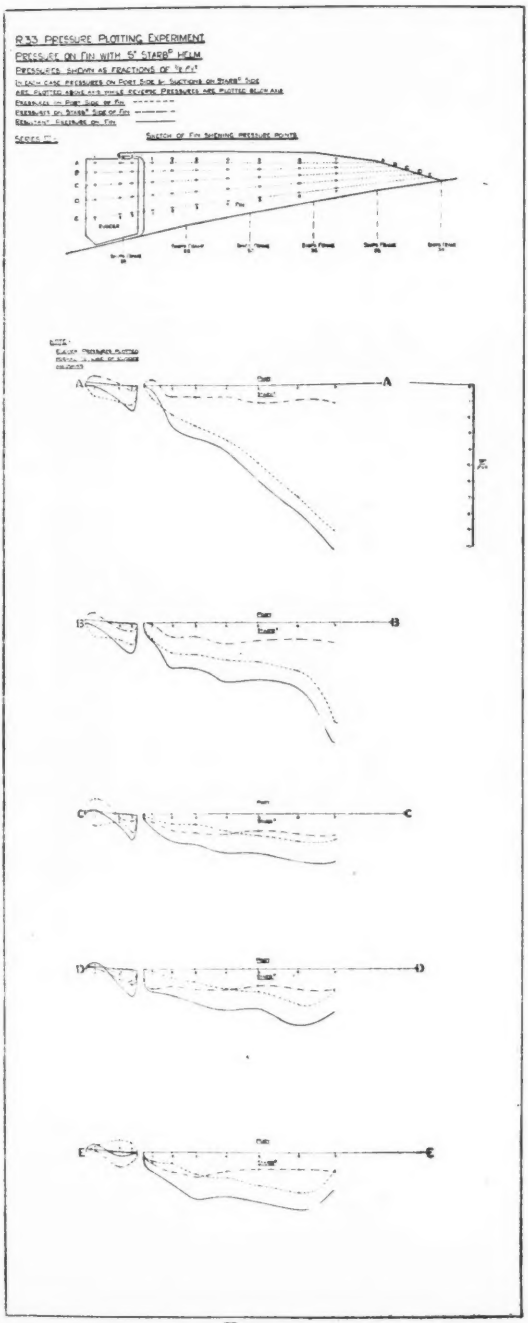

FIG. 5.

Pressure plotting on upper fin and rudder 5° helm.

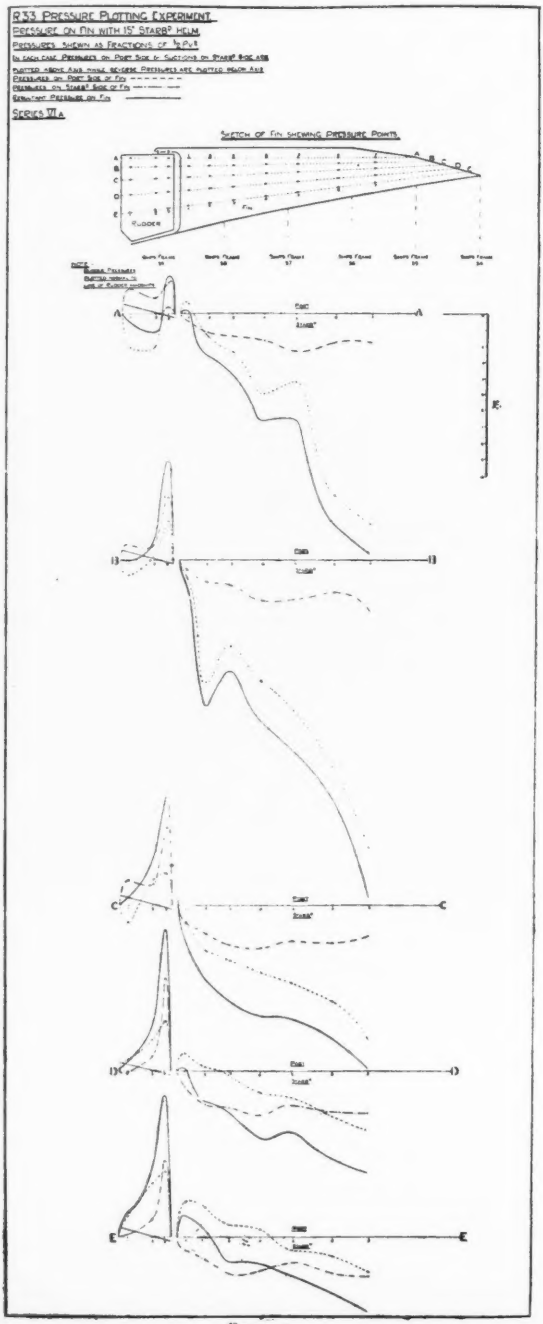

FIG. 6.

Pressure plotting on upper fin and rudder 15° helm.

It was hoped to obtain some records of pressures on R.33 when moored to the mast, but it was found that the pressures varied so rapidly that the present type of instruments would have been quite unsuitable for the purpose. It is hoped to devise an instrument in the future which will deal with rapidly varying pressures. In any case it has been possible to carry out such a complete programme of theoretical and model work on R.101 that it is earnestly hoped that ample opportunity will arise for linking it up with extensive full scale experiment with this airship with improved instruments.

An experiment was undertaken in accordance with the scheme proposed in R. & M. 781 to determine the influence of accelerated motion of an airship on

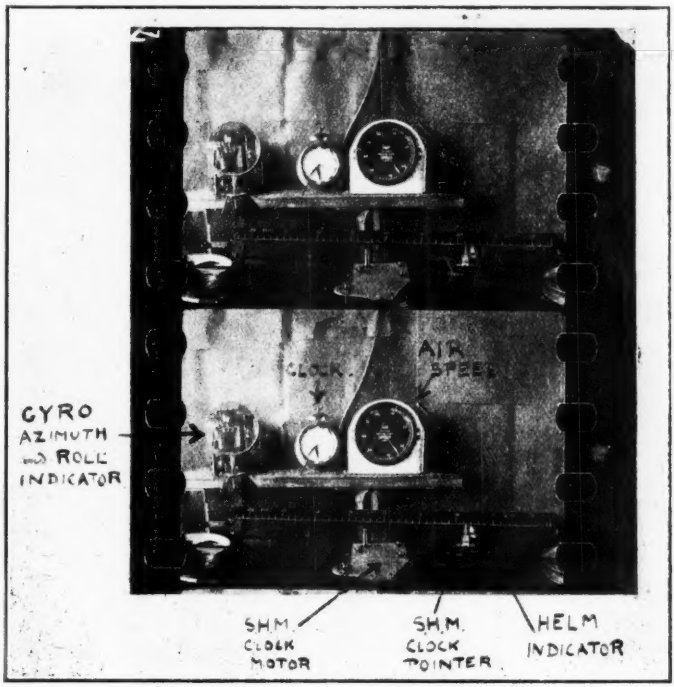

FIG. 7.

Cinema photo in control car—" Virtual Mass Experiment."

the aerodynamic forces acting upon it. This is known as a " virtual mass " effect, since it can be represented by an increase in the mass of the ship called virtual mass. The experiment consisted of operating the rudders in simple harmonic motion and observing the resulting motion of the ship. By comparing this with the motion calculated by the method of R. & M. 781, the effects of acceleration may be deduced. The important quantities for observation in the experiment are the momentary values of angular velocity and yaw.

The operation of the rudders in the desired manner was arranged for by means of a gramophone motor, which, through a simple mechanism, moved a light pointer to and fro over a 30in. scale in S.H.M. A similar pointer was connected by " tell-tale " leads to the rudder and moved over the same scale.

It was the duty of the coxswain to keep the two pointers together, and this was found to be practicable.

By adjusting the governor on the spring motor it was possible to vary the period of oscillation, and a variable throw crank enabled different amplitudes of rudder motion to be obtained. A cinema camera recorded the motion of both pointers. In view of this camera were also a clock, a gyro azimuth and roll indicator and an airspeed indicator (see Fig. 7).

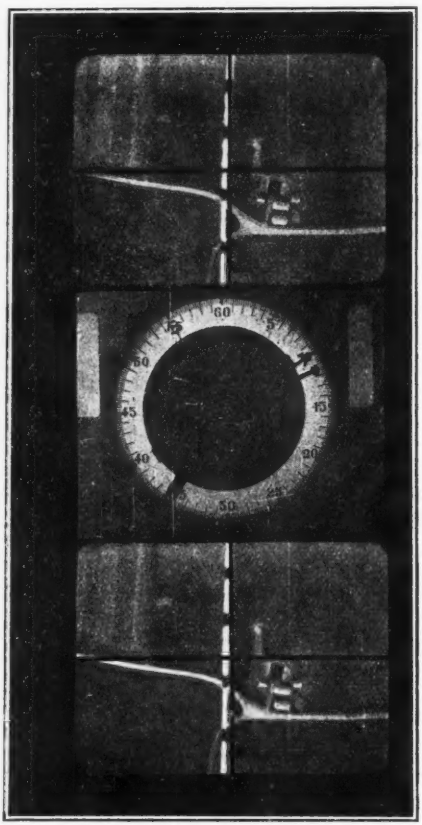

FIG. 8.

Cinema photo of ground—" Virtual Mass Experiment."

A second camera took records of the position of a light cord attached to the apex, 18in. below the hull, of a wire pyramid, kept taut by a weight. This camera had its axis vertical and photographed a watch at the same time. The watch was compared with the clock mentioned above, shortly before and after a test. This second camera also photographed the ground and thus provided records of azimuth in addition to those of the gyro from which the angular velocity could be deduced (see Fig. 8).

As a further check, photographs of the ship were taken from the ground

at intervals of about ten seconds, cross wires fixed 80ft. above the ground providing a datum. This, however, was only a partial success owing to the difficulty of commencing the evolution in such a direction as to accomplish a good portion of it within the field of the camera.

It was found that owing to a bias of the ship in favour of turns to port the resulting motion was sinusoidal with a superimposed turn. It is hoped to be able to deal with this in calculation. The reduction of results has only recently been commenced and the success or otherwise of the experiment and method is not yet known.

(3) *Distribution of Stress in the Hull Framework of a Rigid Airship*

(3A) *Theoretical Work*

A summary of the theoretical work carried out since the war in this country on the stress distribution in the hull framework of a rigid airship will be found in the report of the Airship Stressing Panel[9] and the report of the Airworthiness of Airships Panel.[10] Both these papers contain appendices giving a bibliography of such other subsidiary papers as have been published on the same subject.

Since these papers were published an opportunity has occurred for studying pretty fully their practical application to the case of a specific design. It must, of course, be realised that the papers in question deal with the structure of the rigid airship as it was known at the time that they were written. Since then, however, it has appeared desirable to modify the arrangement of the structure. These modifications have been of two kinds. Firstly, as the Panel has pointed out, certain changes which do not appear in any way harmful might be made in the nature of the structure so as to make it more amenable to mathematical treatment, and therefore to make the knowledge of the stress distribution much more determinate. Changes of this kind have been pushed to the utmost limit in the case of the design of R.101. Secondly, there are modifications of an entirely novel character, as for example those necessitated by the enormous increase in diameter as compared with previous ships. These, of course, could not be foreseen by the Panel, and an account of the appropriate stress analysis must wait for some future date.

In the interpretation of the methods advocated by the Panel certain difficulties arise, most of which have, however, been subsequently cleared up. As, however, it is hoped that a paper will shortly be published by Mr. R. V. Southwell, bringing the work of the Panel up to date, it is only necessary to touch on those matters very briefly here.

The formulæ given by the Airship Stressing Panel are based on the assumption that the shell of the hull is truly redundant in that in every panel there are a pair of bracing members, both of which are operative.

For these to hold under all conditions it is of course necessary to initially tension the wires to an amount equal to the maximum load likely to be imposed upon them. From a practical point of view, at any rate with the Zeppelin type of structure, this is a theoretical condition which it is impossible to achieve. Experience shows that it is not practical to set up all the wires in the hull simultaneously with a known degree of initial tensioning. Moreover, in the process of time, presumably owing to the flattening of the wire loops, the bending of wiring plates, and the development of general slackness in the joints, the initial tension becomes reduced. It is possible, I think, to design the structure so that this deterioration in wire tensions is very radically reduced. At the same time it appears doubtful if it is a wise policy to carry the initial tensioning to that degree which would ensure that no bracing wire ever becomes inoperative.

[9] R. & M. 800.

[10] R. & M. 790.

It is, of course, understood, though not specifically mentioned by the Airship Stressing Panel, that the stresses caused by the self-straining of the structure under this initial tensioning must be added to the stresses set up by external actions. These self-straining stresses may be of quite considerable magnitude, if the initial tensioning is carried to the degree indicated. Fortunately, if under the action of some lesser initial tensioning some of the wires become inoperative, it still appears possible to apply the methods of the Panel with the addition of a correction for the inoperative wires, according to a method suggested by Mr. Southwell, and which has received experimental verification on model tests by Professor Pippard.[11]

The generalised formulæ developed by the Panel are based on the assumption that the bulkheads are sufficiently stiff for St. Venants principle to be rigidly applied to any particular bay. In other words, the external actions at the two ends of a bay entirely determine the distribution of stresses within that bay. If a generalised formula is to be used and not a method employing impossibly laborious calculation, this appears to be the only assumption on which to form a workable method. How accurately it applies, however, in the case of any specific structure must to a certain extent be a matter of speculation. This matter is further discussed below in connection with the model and full scale work which is being carried out.

(3B) *Model Work*

A full description of the experiments which have been in progress on the investigation of stress distribution in model airship frameworks was given by Professor Pippard to this Society as recently as January last, and therefore needs but little comment here.

The properties which the Airship Stressing Panel were obliged to ascribe to an airship's structure in the application of their methods have already been commented on. It is easier in my opinion to make the model conform to the type of structure required by theory than it is to make the actual airship do the same, as for example in the matter of providing pin joints and a known amount of initial tension in all wires. Further, by varying the rigidity of the bulkheads in the model it was possible to show, at any rate in a qualitative manner, the influence of such variation on the strict application of St. Venants principle as used by the Stressing Panel. As I visualise the position reached it appears to me that it may be summarised as follows. In so far as the model agrees with the structure postulated by the Stressing Panel it gives, as might be expected, good confirmation of the panel's formulæ. It goes further than this, however. It shows (in the more recent experiments) that in applying the Panel's theories to the actual ship's structure too much attention need not be paid to the fact that joints are fixed instead of being pin-jointed. This is fortunate, since perfect pin joints would be expensive and somewhat heavy to provide in the hull of a rigid airship. Apparently, however, it is thought worth while by Italian designers for the keels of their semi-rigid airship.

The model also shows that the difficulty encountered when one bracing wire goes slack may with considerable confidence be dealt with by the method suggested by Mr. Southwell. On the more difficult question of the application of St. Venants principle, however, the model can do no more than warn us that this is very much a matter of the relative elastic properties of the bulkhead and shell in the particular structure under consideration. It would be very difficult if not impossible to make a model to imitate the hull structure quantitatively in this respect, and hence this point must be dealt with by experiment on the full scale structure if possible, which brings us to a discussion of full scale stress distribution experiments.

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[11] *See* R. & M. 971.

(3c) *Full-Scale Work*

It became clear at an early stage in our work that very little attention had been paid to the possibility of investigating internal stress distribution by means of experiments on the actual full-sized structure. If it were possible to record the strains in the members of the ship during flight, a very valuable check on the theories underlying the design would be obtained. If a sufficient number of records covering all types of manœuvres, especially in gusty weather, could be obtained, it would be possible to estimate the actual factors of safety existing in the various members. This would provide the only really safe means of deter-

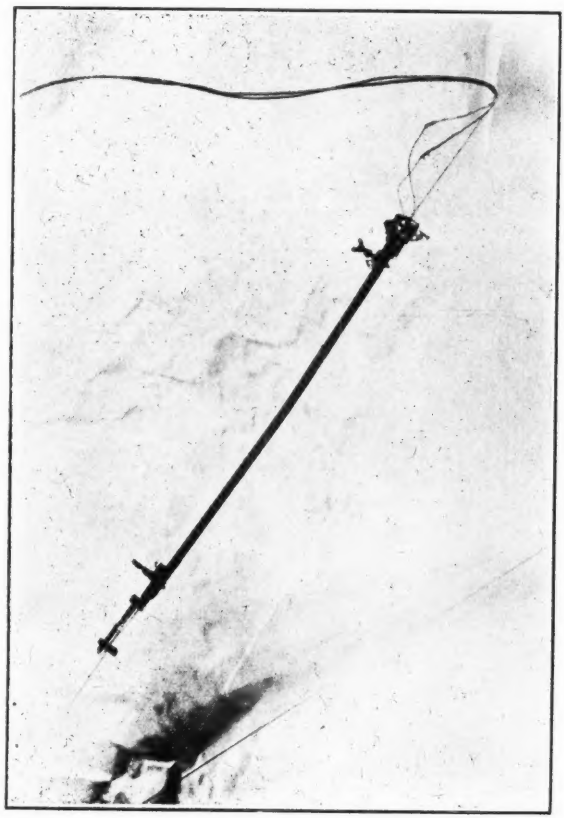


FIG. 9.
Strain gauge fixed on bracing wire.

mining how far weight could be saved and the design refined in future vessels of the same class.

The need for a suitable instrument for the purpose became apparent, and with the assistance of Professor C. F. Jenkin, Mr. E. B. Moulin and the Cambridge Instrument Co., considerable success has been achieved in this direction.

Each instrument is in effect an extensometer, in which the changes in length of the girders or wire bracings under varying loads may be measured at a distance. Each instrument consists of a number of elements which can be assembled in different ways, according to the purpose for which the instrument may be required. The principal part is the electric choke coil with variable air gap, which measures the extension or compression. It is quite light and only a few centimetres long. An extension piece is fitted to the choke by a clamp. A variety of extension pieces has been provided, whose length is chosen to suit the sensitivity required, and the material of which can be either steel or duralumin

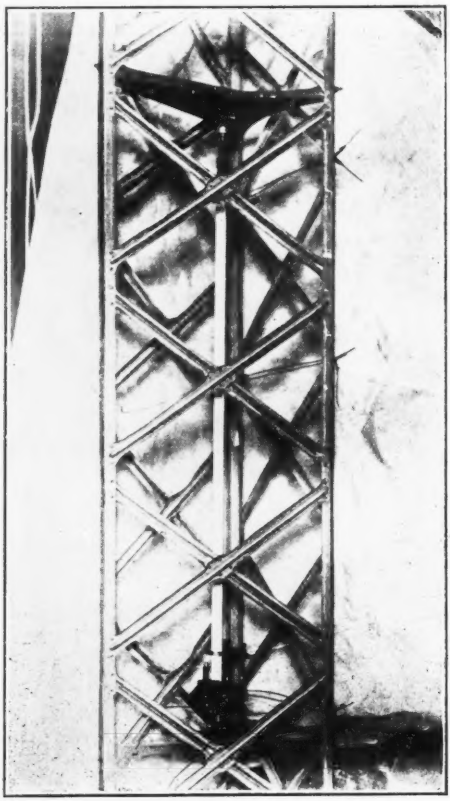


FIG. 10.
Strain gauge fixed in girder.

so as to avoid spurious effects due to change of temperature. Suitable ends are clamped to the instrument for use on a wire or else on the neutral axis of a girder, for which latter purpose ball joints are provided. Alternative clamps for fitting the gauges in the individual booms of the girder can be provided. An illustration of the instrument attached to a wire is given in Fig. 9, and of the instrument attached to a girder in Fig. 10. When the extensometer is fitted to a member under test, the air gap in the electromagnet or choker varies directly with changes in length and so with the stress in the member. When

an alternating current of constant ratio of voltage to frequency is applied, the reactance and consequently the current through the electromagnet varies lineally with the air gap (for small gaps) and hence with the strain in the member.

Various means for measuring the current changes have been adopted. If the load is not of a rapidly varying character, a Duddell thermo-ammeter may be used, the scale of which is calibrated to correspond with the air gap. Direct readings of .005 mm. can be made so that the instrument is very sensitive but it is not sufficiently robust for certain purposes and the calibration is liable to change. An alternative is to use a buzzer as a source of current, and to connect up the extensometer Wheatstone-Bridge fashion, with a standard choke in the opposite arm of the bridge, the air gap of which can be varied by means of a micrometer screw. Balance is obtained before and after the load is applied by

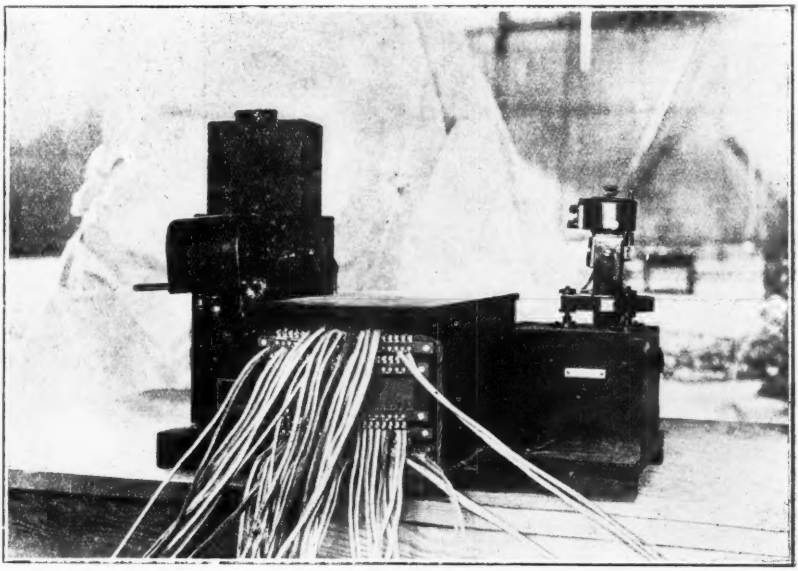


FIG. 11.
Oscillograph strain recording apparatus.

turning the micrometer screw and listening for zero sound in a telephone connected across the arms of the bridge. The instrument can be read accurately to between .01 and .02 of a millimetre. A total strain of 1 mm. represents about one-fifth of the yield stress for steel or duralumin on a metre length, and therefore the accuracy is .2 of 2 per cent. of the yield stress. There is an additional error possible of about .1 per cent. on reading the gauge length and a variability amongst various gauges of perhaps 1 per cent. This latter could, of course, be avoided by calibrating all the gauges in a micrometer measuring machine.

A third method of recording the current when the strain in the member is varying rapidly is by means of an oscillograph. The apparatus is shown in Fig. 11. A small motor fed by a 12-volt battery drives the generator and also a commutator switch by means of which 40 gauges and two standard gaps for calibration can be put in circuit in turn, the whole cycle taking about 4½ seconds

to complete. The deflections of the oscillograph are recorded photographically, a typical record being shown in Fig. 12. The accuracy obtainable with the instrument is of the same order as that for the instrument just described above.

To interpret properly the records of strain given by these instruments it is necessary that the member being tested should have been calibrated for stress and strain in a testing machine, preferably with one of the instruments in place. It has now been made a routine matter to insert one of these gauges during all girder tests so that when it is possible to fly the new airship with the instruments in place it should be easy to interpret the results as compared with any attempt to do so on one of the existing airships which would be costly and difficult.

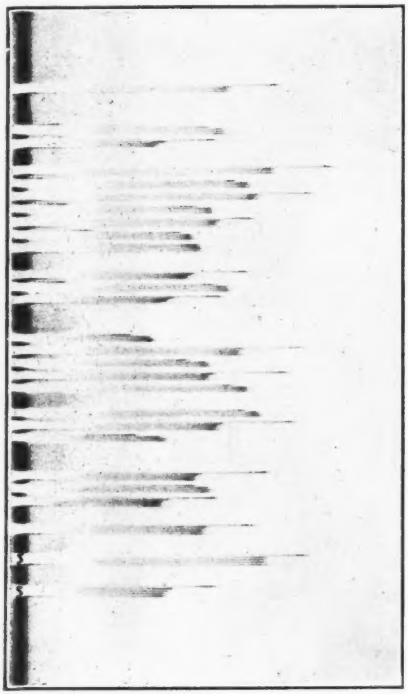
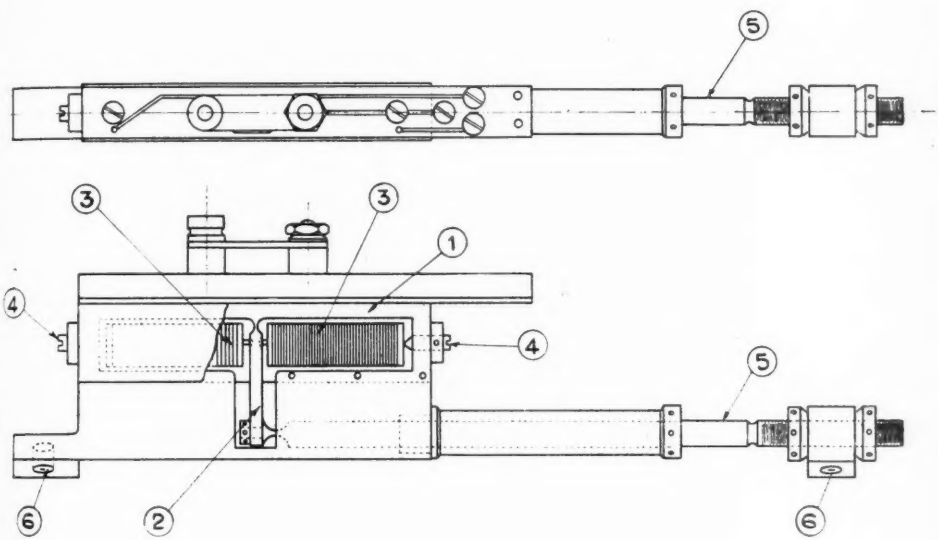


FIG. 12.
Typical photographic record.

The credit for the first attempts to measure strains in airship girders during flight belongs to the American Naval Airship Service. Valuable work has been done in the recording of strains during steady flight conditions. An extensometer working on a somewhat different principle to the British one has been evolved in America.

The American instrument is of the carbon-pile type and is illustrated in Fig. 13. At present it appears to have been arranged only to fit on the individual channels of lattice girders. Two carbon stacks are used and a change in length of the member to which they are secured increases the pressure on one stack and decreases the pressure on the other. In order to utilise the change of resistance of the stacks, they are made two of the arms of a Wheatstone Bridge,

with fixed resistances for the other two arms. The changes in current flowing across the bridge are recorded either by a milliameter or an oscillograph. The range of the instrument is about .012in. on a gauge length of 8in. The accuracy obtainable appears to depend somewhat on the working conditions. It is stated that when conditions are favourable, errors in reading strain need not exceed ½ per cent., while under unfavourable conditions the errors do not ordinarily exceed 5 per cent. This presupposes that the instruments have been properly aged and that they are handled by those experienced in their use.



1. Steel Frame
2. Tongue Piece
3. Carbon Discs.
4. Set Screws
5. Thrust Rod
6. Clamp for Channel Booms

Fig. 13.

Strain gauges in the bow of R.33—forward end.

Some applications of the use of these instruments in full scale investigations will now be described. In the first place, the difficulty of dealing theoretically with the aerodynamic loading arising from disturbed air conditions such as gusts has already been mentioned. The possibility of recording rapidly varying strains in a large number of members by means such as those described above provides some hope at least of dealing in due course with the all-important problem of making an airship sufficiently strong to resist the forces met with in gusty air. No other reliable means appear to exist at present.

An interesting application of the use of strain gauges which has been made both in this country and in America is for the purpose of estimating the forces acting on the bow of an airship when moored to a mooring mast. Use is made of the distortion which occurs in the central spindle which carries the mooring coupling. The strain gauges fixed in the nose of R.33 are illustrated in Figs. 14 and 15. Three gauges were fixed to the mooring spindle—two at the opposite

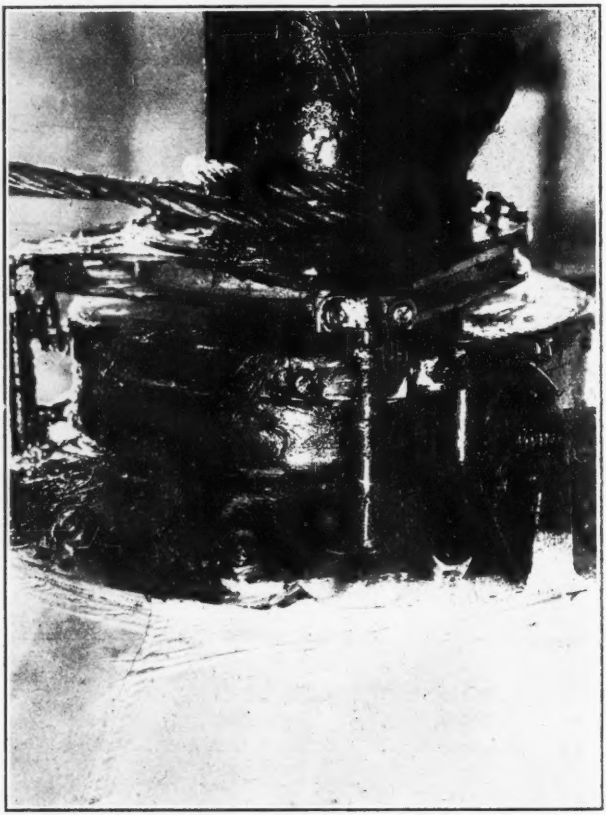


FIG. 14.
American carbon pile strain gauge.

ends of horizontal diameter and one vertically above the centre. The mooring spindle, of course, rotates, and it was unfortunately not possible to allow the strain gauges to rotate with it. In consequence it was necessary to mount them on diaphragms carried on ball races. They functioned very well when the races were first assembled, but as end play developed, false readings were obtained. This will be obviated in future designs by allowing the gauges to move with the spindle. From the readings given on the pair of horizontal gauges, it was possible to estimate both axial and lateral force.

The vertical gauge was connected to a distant reading instrument in the

control car, so that the captain could weigh off his ship by means of this gauge immediately before leaving the mast.

An interesting variation adopted by the Zeppelin Co. for measuring the forces on the bow of the Los Angeles is illustrated in Figs. 16 and 17. The main spindle is surrounded by a light tube which is fixed to the spindle at one end only. In consequence the other end of the tube moves in relation to the spindle when the latter is distorted. This movement is multiplied by a system of levers which carry a small roller travelling over a resistance coil.

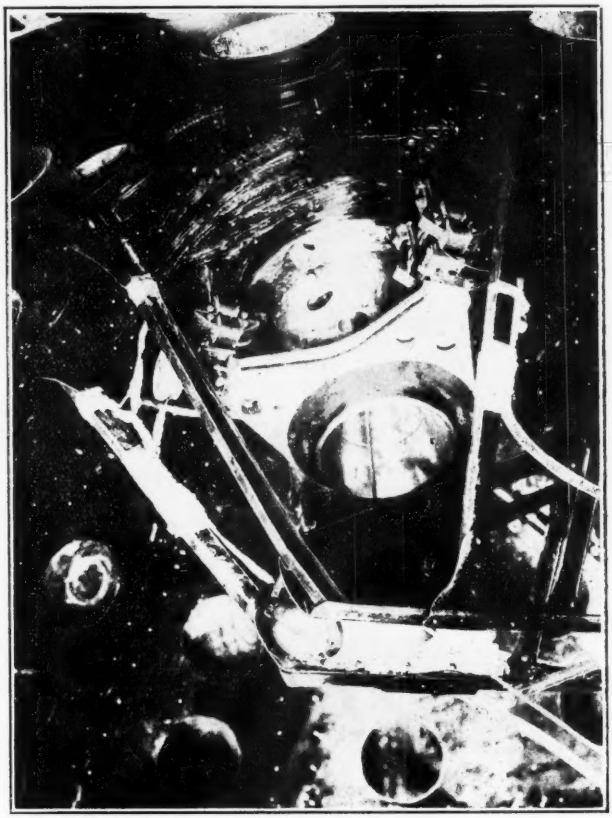


FIG. 15.
Strain gauges in the bow of R.33—aft end.

The degree of accuracy with which the forces on the bow can be ascertained is not known, but an automatic device was installed which indicated when these forces reached what was considered a dangerous magnitude.

The significance of Prof. Pippard's excellent experiments on models in relation to the work of the Airship Stressing Panel has already been commented on. It will be appreciated from what has been said that in certain respects the degree of accuracy with which the stress distribution approaches that worked out by the Stressing Panel depends on the relative elastic properties of the shell

and bulkheads. Since these cannot be accurately imitated in the model, it was thought desirable to repeat the work on a portion of an actual airship.

The only satisfactory fixing which could be made for the portion of the hull was, of course, the ground. It was desirable to have at least three complete bays of the airship in order to test St. Venants principle, and the airship R.80 was chosen for this purpose as being the only one of which three bays could be accommodated within the shed. This is illustrated in Fig. 18.

FIG. 16.

Mooring spindle—"Los Angeles."

The topmost bulkhead is loaded laterally by ropes which pass over pulleys in the roof and carry trays on which weights are placed. The work has unfortunately not yet proceeded far enough for any actual results to be quoted. Secondary effects arise in the ship which are not present in the model, such as the yielding of wire loops and lugs, and uncertainty as to the exact degree of initial tension. After the tests, typical girders are being cut out and calibrated in a testing machine with extensometers fitted in them.

Certain fundamental changes in the design of the bulkheads for the new airship have been adopted, and again it is necessary to have some knowledge

of the relationship between the elastic properties of these bulkheads and the shell of the airship. For this purpose it is intended to carry out loading tests on typical built-up portions of the structure of the new airship to a much more extensive degree than has been attempted in the past. Thus a typical transverse frame has been built which will be loaded in various ways and the internal stresses analysed by means of the strain gauges. This will be linked to a second ring, the whole will be mounted on the door of the shed, and a shear will be applied across the section by filling it with an inflated gasbag. The type of construction is such that the girders can easily be unassembled afterwards and tested individually to destruction in order to assess the degree of variability in strength which arises from inequalities in manufacture.

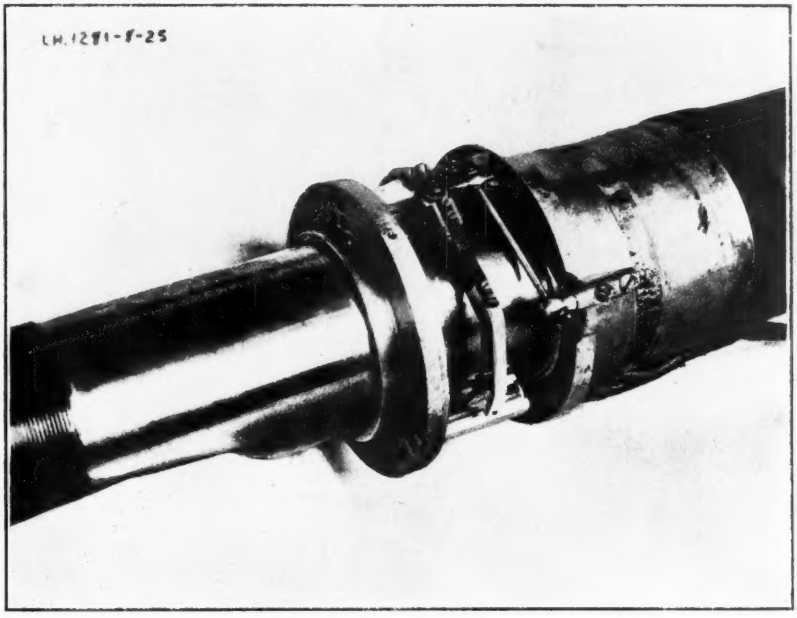


FIG. 17.
Lever and variable resistance gear in Los Angeles spindle.

It would perhaps be appropriate if a word was said here regarding the extensive research which has been carried out with the assistance of Messrs. Boulton & Paul into new designs and methods of manufacture for these girders, especially as the strain gauges have had a most direct and useful application in this respect. By utilising the extensive experience gained in the manufacture of light structural members for metal aeroplanes, Messrs. Boulton & Paul have been able to render most valuable assistance in developing girders which, as I shall presently show, represent a marked increase in efficiency on any which have been used in airship work before.

Some of these girders have now attained such dimensions that it is possible to fit the various elements of the girders with strain gauges, and to measure strains and deflections in all parts of the member. It will be readily appreciated that in the theoretical treatment of the braced and cambered girder, under the

combined action of a complicated system of loads such as end load, side load, and torque, it is very necessary to know the deflections which will occur with any given loading system.

The various cases of loading which must be taken into account in designing the member are so numerous that a calculated result needs to be reliable. A system of calculation suggested by Mr. R. V. Southwell has been developed,

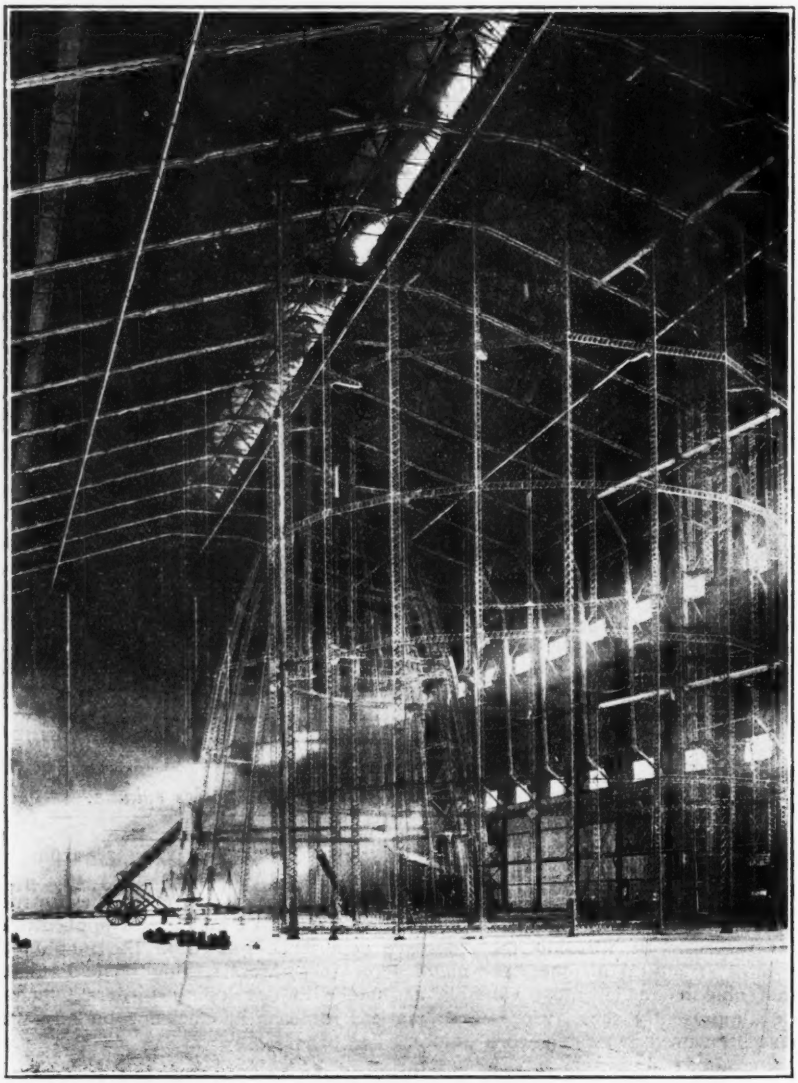


FIG. 18.
Portion of R.80 set up for strain measurement.

and by means of practical measurements of strains and deflections taken as described above, it has received remarkable experimental verification. An example of this for the main longitudinals of the ship is given in Fig. 19, from which it will be seen that the calculated and measured shapes assumed by an initially cambered girder under various loading conditions agree very well indeed.

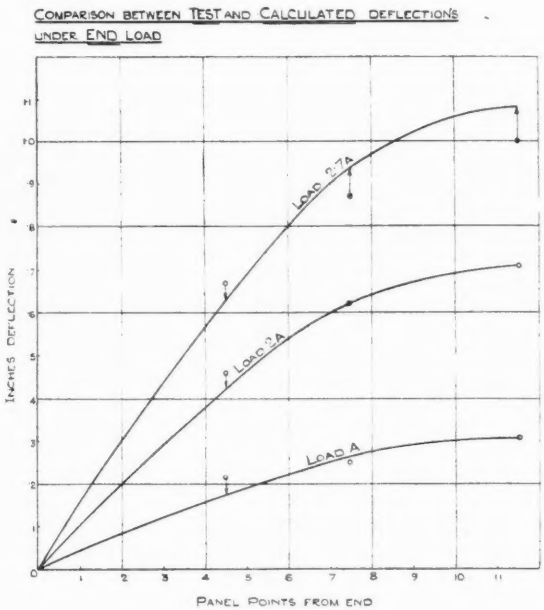


FIG. 19.

Comparison of calculated and measured deflection on a longitudinal girder for R.101.

The importance of this can hardly be over-estimated, since all possible cases which might give rise to failure can be explored when a direct method of design is established. High tensile stainless steel booms (of about 70 tons per sq. in. effective compression strength) are used in conjunction with light alloy members in the shear structure, with all the advantage in structural efficiency to be expected from the higher specific properties. Simplicity of replacement, standardisation and adaptability to any reasonable curvature, without alteration of standards, has been achieved.

A considerable number of the structural members are of course simple struts. In order that strains in such members may be truly calculable, it is necessary that the joints shall be such as to give rise to pure axial loading, and not to give indeterminate end fixing conditions such as exist in some of the complicated built-up joints of the Zeppelin type.

It is also desirable to provide for quick assembly and interchangeability so that the excessive time and cost involved in drilling and riveting up the structure in the shed (most of which work has to be done at a considerable height above the ground) may be avoided.

It is, of course, desired to obtain the lightest members consistent with these requirements, and it must be remembered in any consideration of structural

weight that the weight of the joints as well as of the members must be taken into account.

It will be seen, therefore, that amongst other things, weight will depend on absolute overall dimensions of cross-sections, since these will affect the stresses in the axially-loaded joints. The weight will also depend on the value of the

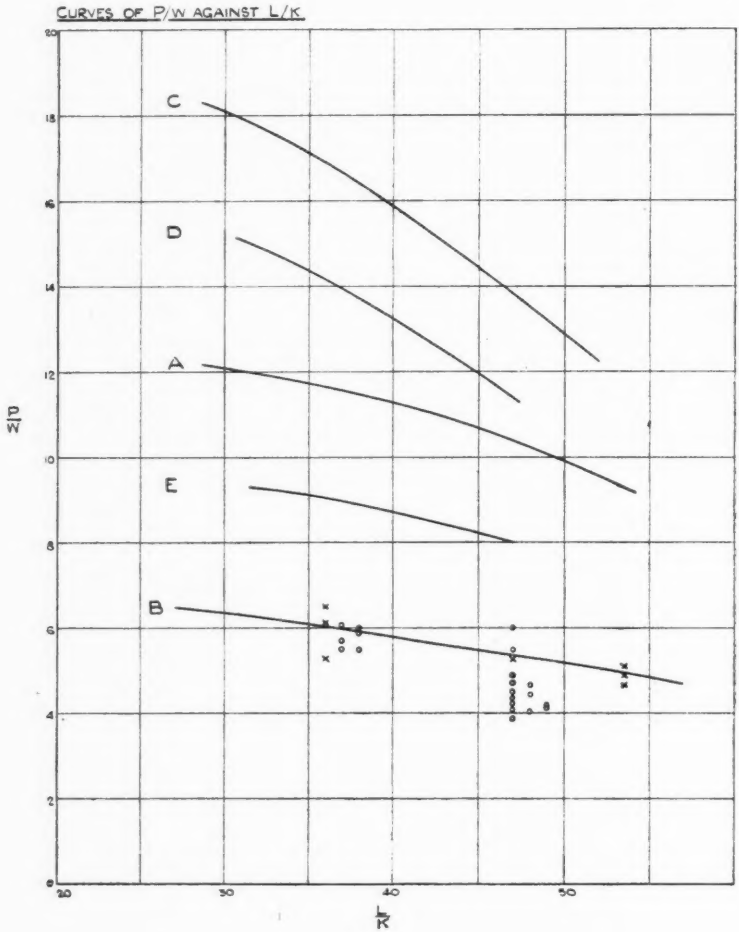


FIG. 20.

Curves illustrating efficiency of various types of strut girders.

slenderness ratio of the member, the specific stresses which the material can sustain, and its specific elasticity.

Dealing with the last points first, it may be stated that the specific effective compressive strength of a suitable steel is, roughly, 50 per cent. greater than that of duralumin, the specific elasticities being about the same: hence the weight-saving possible by the use of steel is enhanced at the lower values of l/k.

In the Zeppelin type of structure, which consists of braced latticed girders, with channel booms, the load which these girders should sustain can be calculated, and dividing this by the total area of the booms and the lattice, a figure can be reached for the mean average stress on the total area as distinctive from the effective area. This may be taken as a figure of merit for various values of l/k. In order to eliminate the density of the material in the discussion of efficiency, it is more convenient to use load divided by weight per foot run.

In Fig. 20, curve A represents duralumin girders of the Zeppelin type, supposed to have 100 per cent. effective area. Curve B is the theoretical curve for the best Zeppelin type girder plotted on the basis described above, and taking into account the actual effective area.

The circles and crosses represent English and American tests on these girders. It is interesting in analysing tests on these girders to note that increasing the lattice work (which bolsters up the channel booms) increases the mean average stress of the effective area, but this tends to be nullified by the reduction of the factor-effective area over total area, giving a somewhat flat-topped curve for the most efficient proportion of lattice to boom.

In the strut girders for R.101 a somewhat radical departure has been made from Zeppelin practice. For the most part the girders are a combination of stainless steel and duralumin, although in very lightly-loaded members the steel parts are completely replaced by duralumin.

The 100 per cent. efficiency curve for the composite steel-duralumin girders is shown at "C." The characteristic actual efficiency curve obtained from these girders is shown at "D." The characteristic efficiency curve obtained for the new type of duralumin girders is shown at "E." It will be seen that for values of l/k between 35 and 45 (which is the range employed), the advance in efficiency over Zeppelin practice for both duralumin and composite girders is very marked indeed. All these members lend themselves to economical detachable joints for axial loading.

It is hardly necessary to add that the general arrangement of the structural members of the ship is part of a harmonious scheme for utilising such efficient members and working within this slenderness range.

Appendix

AN EXAMINATION OF THE EFFECT OF CERTAIN SIMPLE WIND VARIATIONS ON THE LATERAL FORCE EXERTED AT THE BOW OF R.33 WHEN MOORED TO A MAST.

There is undoubted evidence that airships, when moored, are subject to large lateral as well as axial forces. These lateral forces will of course depend on the character of the wind, the chief points of interest being the rate of variation, both of the magnitude and direction of the wind. It is important to pay full attention to both these factors, as experience has shown that winds of comparatively light magnitude, if varying rapidly in direction, may exert more dangerous forces on the airship than steady winds of higher velocity.

Two simple cases have been considered:—

1. A wind of constant linear velocity changing in direction with constant angular velocity.
2. A wind constant in direction increasing from zero velocity with constant acceleration, some initial angle of yaw being assumed.

Step by step integration is employed. Acceleration derivatives have been ignored, a fact which implies that the results are approximate only. A mean

value of the derivative CNr/V (N.P.L. notation), independent of yaw, has also been assumed.

Let V = wind speed.
,, C = moment of inertia of ship about a vertical axis through the C.G.
,, $I = C + mL^2$, where m is the mass of the ship and L is the distance from vertical axis of mast to C.G.
,, θ = azimuth of ship.
,, ϕ = azimuth of wind.
,, $\beta = \phi - \theta$ = angle of yaw.
,, CN_β = moment about C.G. at yaw β.
,, mY_β = lateral force at yaw β.
,, $mY_\beta L - CN_\beta$ = moment about bow at yaw $\beta = M_\beta$ say.
,, CN_r = rate of change of moment with angular velocity of ship relative to wind where $r = \partial\beta/\partial t$.

Case I.

Constant wind speed V and constant $\partial\phi/\partial t = A$. Taking moments about the mooring point,

$$I \cdot \partial^2\theta/\partial t^2 = M_\beta - \partial\beta/\partial t \cdot CN_r \quad . \quad . \quad . \quad . \quad (1)$$

(the value assigned to CNr is negative.) Values of M_β/V^2 and CNr/V are available from model data. Values for M_β/V^2 are taken from R. & M. 361 (corrected by Jones, 29.4.25). The value of CNr/V varies with β. A mean value of -10^6 has been adopted.

Integrating (1) over a small time interval δt,

$$I\,(\partial\theta/\partial t) = M_\beta \delta t - \delta\beta \cdot CNr + I\omega \quad . \quad . \quad . \quad . \quad (2)$$

Where ω is the value of $\partial\theta/\partial t$ at the commencement of the interval δt.

Integrating again,

$$I\delta\theta = M_\beta\,(\delta t)^2/2 - CNr\,(\delta\beta \cdot \delta t/2) + I\omega \cdot \delta t \quad . \quad . \quad . \quad (3)$$

but

$$\delta\theta = \delta\phi - \delta\beta = A \cdot \delta t - \delta\beta$$

$$\therefore \tfrac{1}{2} \cdot M_\beta \cdot (\delta t)^2 - [I \cdot (A - \omega) + \delta\beta/2 \cdot CNr] \cdot \delta t + I \cdot \delta\beta = 0 \quad . \quad (4)$$

Assuming an initial value of β and putting in (4) a definite small value of $\delta\beta$ and the corresponding value of $M\,(\beta + \delta\beta/2)$ the mean moment due to yaw for the interval, the quadratic equation may be solved for δt.

Two real and positive roots may be obtained. Of these the smaller is the desired one. (The larger represents the time taken for the angle of yaw to increase from β_0, through $\beta_0 + \delta\beta$, up to some maximum value, and return to the value $\beta_0 + \delta\beta$, were the moment to remain constant at the mean value adopted.)

Substituting the value of δt thus found in equation (2) gives the value of ω at the end of this step and the commencement of the second.

As a check on each step, the arithmetic mean value of ω for the step multiplied by δt should agree with the value of $\delta\theta$ $(= A \cdot \delta t - \delta\beta)$ assumed.

This method is found practicable and results obtained are shown on the accompanying curves.

Equation (4) shows that if A, $\sqrt{M_\beta}$ and CNr are simultaneously changed in the same ratio, the motion will be similar, the time scale alone being affected; that is to say, the yaw is a function of V/A, because $\sqrt{M_\beta}$ and CNr are both proportional to V.

The step by step calculation has been performed for four values of V/A and the maximum angle of yaw and corresponding (lateral force/V^2) have been plotted against V/A.

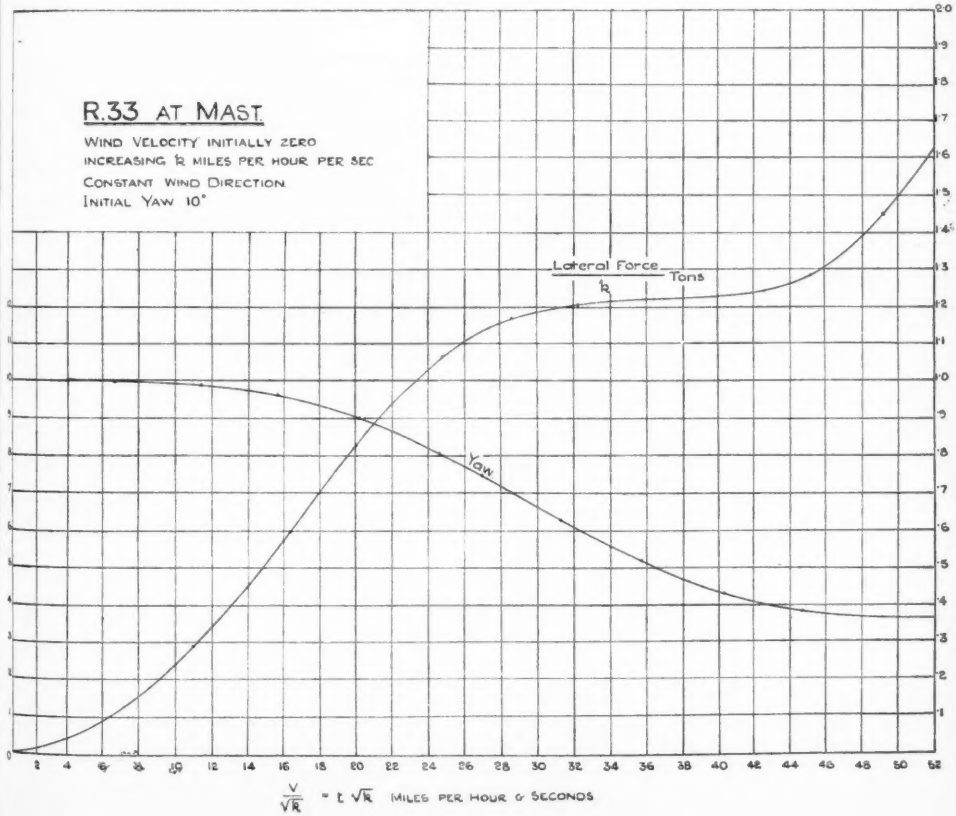
In these calculations an initial value of β of $4\frac{1}{2}°$ has been assumed. This is a position of zero moment about the bow in a steady wind. If the initial value of β were $0°$ or $-4\frac{1}{4}°$, it can be foreseen that the maximum yaw would be less for the same value of V/A in the case of R.33 (owing to the predominance of the "damping" moment at small angles of yaw). Therefore the initial conditions taken are the most severe ones.

CASE I.

RATE OF CHANGE OF DIRECTION OF WIND: DEGREES/SECOND.

Wind Speed. m.p.h.	1. Yaw degrees.	1. Lateral Force. Tons.	1½. Yaw degrees.	1½. Lateral Force. Tons.	2. Yaw degrees.	2. Lateral Force. Tons.	3. Yaw degrees.	3. Lateral Force. Tons.	4. Yaw degrees.	4. Lateral Force. Tons.
30	9.5	2.0	11.7	2.7_5	13.9	3.5_5	(18	5.0_5)	—	—
40	(8.3	2.9)	10	3.9	11.7	4.9	14.9	6.9_5	(18	9.0)
50	(about $7\frac{1}{2}$)	(about 4)	9	5.1_5	10.4	6.4	13	8.9_5	15.5	11.5
60	(about $7\frac{1}{4}$)	(about 5.4)	(8.3	6.5)	9.5	8.1	11.7	11	13.9	14.2

(Figures in brackets have been extrapolated.)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INITIAL YAW 10°
Lateral Force / ½ Tons
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V/√R = t √R MILES PER HOUR & SECONDS

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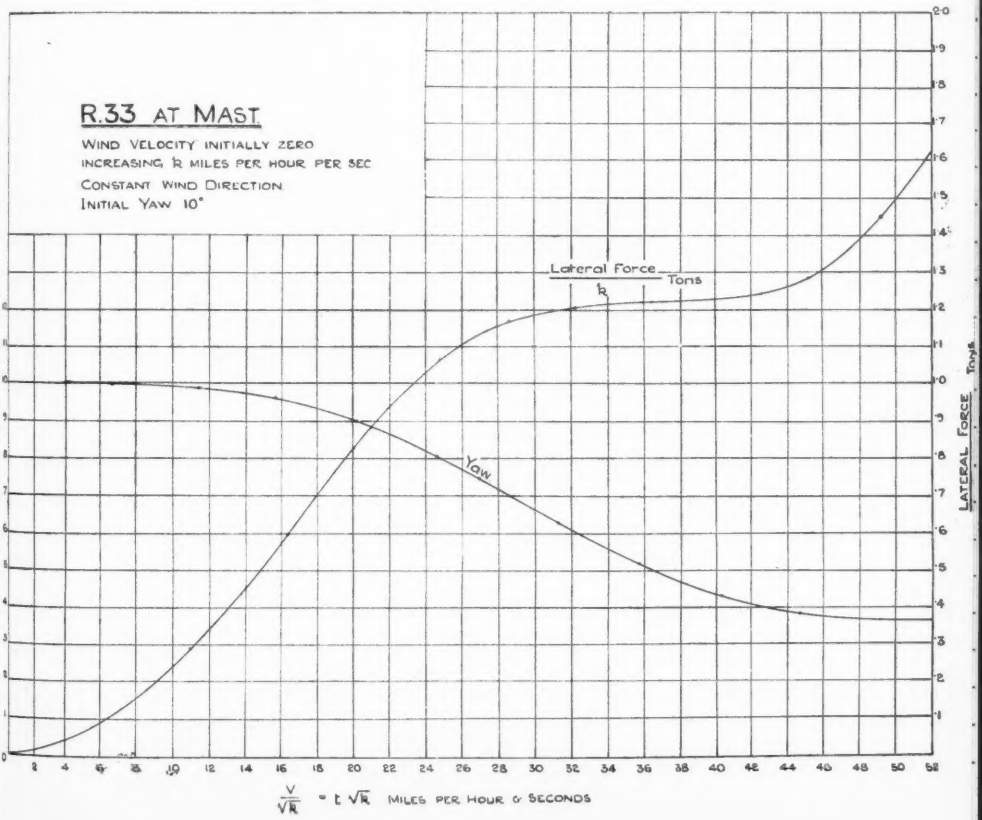
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CONSTANT WIND DIRECTION
INITIAL YAW 10°
Lateral Force / k Tons
Yaw
LATERAL FORCE Tons
V/√k = t √k MILES PER HOUR & SECONDS

Case II.

CONSTANT WIND DIRECTION, LINEAR INCREASE OF WIND SPEED WITH TIME.

$$\partial\phi/\partial t = 0$$
$$V = kt$$

Since M_β varies as V^2.

Let $M_\beta = m_\beta V^2 = m_\beta \cdot k^2 t^2$ where m_β depends only on β, and since CNr varies as V, let

$$CNr = QV = Q \cdot kt \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Thus the equation for moments about the bow becomes

$$I\,(\partial^2\theta/\partial t^2) = m_\beta k^2 t^2 - (\partial\beta/\partial t)\,Qkt$$

Whence, after a small time interval δt

$$I\,(\delta\theta/\delta t) = m_\beta k^2\,[t^2 \cdot \delta t + t\,(\delta t)^2 + (\delta t)^3/3] - Qk \cdot \delta\beta\,(t + \delta t/2) - I\omega \quad . \quad (6)$$

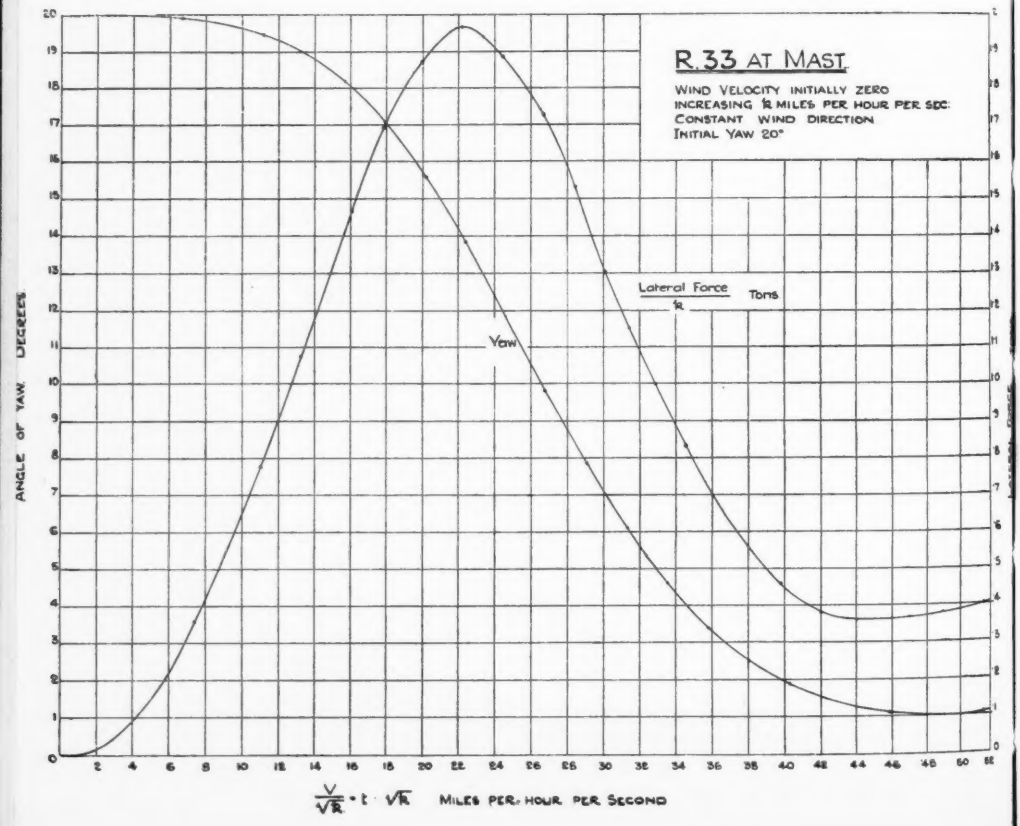
Where ω is the value of $\partial\theta/\partial t$ at the commencement of the interval δt and

$$I \cdot \delta\theta = m_\beta k^2\,[t^2\,(\delta t)^2/2 + t\,(\delta t)^3/3 + (\delta t)^4/12] - Qk \cdot \delta\beta\,[t\,(\delta t/2) + (\delta t)^2/6] + I\omega\delta t = -I\delta\beta \quad . \quad . \quad . \quad (7)$$

or

$$-\delta\beta = \frac{m_\beta k^2\,[t^2\,(\delta t)^2/2 + t\,(\delta t)^3/3 + (\delta t)^4/12] + I\omega\delta t}{I - Qk\,[t\,(\delta t/2) + (\delta t)^2/6]} \quad . \quad . \quad . \quad . \quad (8)$$

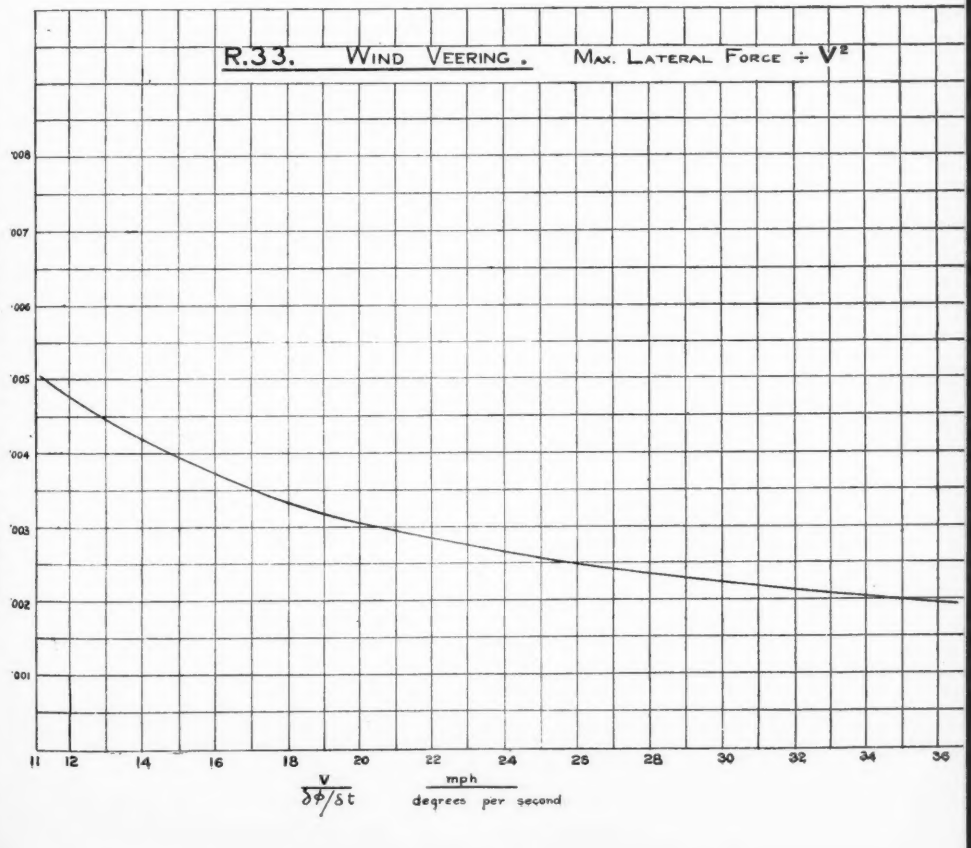
Equation (8) may be solved repeatedly by trial and error. A small value of δt is inserted and a mean value of m_β has to be guessed. In practice it is found that two trials at most suffice and that one is often sufficient.


R.33 AT MAST
WIND VELOCITY INITIALLY ZERO
INCREASING ½ MILES PER HOUR PER SEC.
CONSTANT WIND DIRECTION
INITIAL YAW 20°
Lateral Force ½ Tons
Yaw
ANGLE OF YAW. DEGREES
LATERAL FORCE ÷ V² Tons/(mph)²
V/√k = t · √k MILES PER HOUR PER SECOND

This equation shows β to be a function of kt^2, so that for a given initial yaw β_0, the yaw can be plotted against $\sqrt{k}t$ or $V/\sqrt{k}$, and since yaw determines (lateral force/V^2) values of (lateral force/k) can also be plotted against $\sqrt{k}\,.\,t$ or $V/\sqrt{k}$. This has been done for values of the initial yaw of 10° and 20°.

CASE II.

k= acceleration of wind in m.p.h. per second.		First peak value of lateral force, and wind speed at which it occurs.		Lateral force on reaching 70 m.p.h. tons.	Ultimate value of lateral force in a steady wind of 70 m.p.h. at 41° yaw.
		m.p.h.	tons.		
1	Initial yaw 10°	26	1.1	(about 3.5)	
	" " 20°	22	2.0	(? but less than 3.6)	
2	" " 10°	37	2.2	2.9	
	" " 20°	31½	3.9	0.8	
3	" " 10°	45	3.3	3.7	
	" " 20°	38½	5.9	1.3	3.6 tons.
4	" " 10°	52	4.4	4.9	
	" " 20°	44½	7.9	3.1	
5	" " 10°	58	5.5	6.0	
	" " 20°	49½	9.9	5.8	



Conclusions

The curves for Case I. have been taken as far as the maximum yaw only, the subsequent gradual decrease of yaw to the stable value of $4\frac{1}{4}°$ being unimportant.

From the results for Case I., values of maximum yaw and corresponding lateral force are tabulated for various wind speeds and rates of change of wind direction.

The curves, Case II., for 10° and 20° initial yaw respectively, have been pursued until the yaw has reached a minimum and just started to rise again toward the final stable angle of $4\frac{1}{4}°$. It may be noted that when the initial yaw is 20°, the stable position is overshot by some 3°; whilst when the initial yaw is 10°, the stable position is only overshot by about $\frac{1}{2}°$. This is the cause of the considerable difference between the lateral force curves for the two values of initial yaw. For some value of the initial yaw greater than 20°, the ship would no doubt swing past the position of zero yaw and finally come to rest at $-4\frac{1}{2}°$.

Values of lateral force are tabulated for various values of k, the rate of increase of the wind. The values given are those occurring at the first peak, those occurring when the wind reaches 70 m.p.h. and finally, for comparison, the ultimate value in a steady 70 m.p.h. wind. The lateral force at the first peak is of chief interest and importance.

Discussion

Air Vice-Marshal Sir W. S. Brancker: I will open the discussion by congratulating Colonel Richmond very heartily on the very wonderful progress his department has made in the design of rigid airships. We have just seen from the curves on the screen that not only will R.101 be considerably stronger than the airships of the past, but she will also work out much lighter. There is no doubt therefore that she should prove to be by far the most efficient rigid airship ever built.

I would like Colonel Richmond to tell us his opinion of the American proposals to construct an all-metal airship. I used to pooh-pooh this idea, but when I was in America the other day I visited the works, and talked to the designers, of this new system, and I must I was quite impressed. The designers claim that for any ship of 1,600,000 cubic feet and over they will actually save weight on existing designs of rigid airships. We must remember that they are basing their claim on Zeppelin practice in the past.

Colonel Richmond has told us of the difficulty of calculating the strength of the gusts which an airship may have to encounter. I should like him to tell us whether it is not possible to calculate gusts by means of the pressure plotting tubes already fitted to R.33.

Group Captain P. F. M. Fellowes said: There are two points which have struck me. One is the very broad outlook which Colonel Richmond has brought to bear on the problems he has to face, an outlook which leads to generous acknowledgment of assistance received with its natural result, loyal and whole-hearted co-operation. There is no stone which he seems to leave unturned or source untapped in obtaining information which he thinks may make R.101 more perfect.

The second point is that it is satisfactory to discover that the model results apparently impose more drastic conditions to be met than do the full scale results.

Another point which does not arise out of the lecture but to which I should like to draw attention, is that he is fortunate enough to have Major Scott sitting in his pocket to help him on the practical side. I should think it must be almost unique for the designer of so large a vehicle as an airship to have the practical man so close at hand, that daily discussions can take place on any point which arises. I will not occupy any more of your time as I know how anxious Colonel Richmond is to hear the criticisms of the learned members of this Society.

Mr. HUMPHREY PARKER: It has been most interesting to hear from Colonel Richmond's paper the very thorough manner in which the development work and design of R.101 is being handled. The curve showing the gains from the new type girders is particularly striking. The proposed use of composite steel-duralumin girders, however, raises the question of possible corrosion of the duralumin at its points of contact with the steel, due to electrolytic action.

The lecturer's paper has dealt with a phase of research and experiment that is essential to safety in bridging so large a gap as that between ships of existing sizes and the new one; adequate strength for the structure under any conceivable emergency must take precedence over everything else. Research in airships, however, is not limited to the structure only; there are other phases, and though these may not be essentials, they may lead to developments of very great importance. For example, research may lead to the reduction of losses at present accepted as necessary from the use of dynamic lift, from the carrying of ballast, and from the valving of gas due to the burning of fuel. There is one development in this field that has recently been receiving a considerable amount of attention and that offers interesting possibilities. I refer to water recovery. I happen to have been associated with some of the recent work in America, so perhaps a few remarks on what has been done over there may be of interest.

It might first be pointed out that the water recovery problem, in its application to a helium-filled ship using petrol engines, is a somewhat different matter from its application to a hydrogen ship burning heavy oil. In the former case 100 per cent. recovery is fairly easily attainable and is a result that is almost essential to satisfactory operation; in the latter, it is not practically attainable under average conditions. In the helium ship conservation of lifting gas is the primary consideration, the manufacture of landing ballast being an incidental advantage; in the hydrogen ship the manufacture of ballast is more important than the gas saved by the recovery of the last 20 or 30 per cent. of water.

The problem of equipping the Shenandoah was taken in hand in 1923, and as the ship was already flying, results had to be attained as rapidly as possible. The first completed unit was delivered ready for installation four months from the inception of the design. It was not possible therefore to achieve much in the way of refinement, and the resulting apparatus was somewhat crude aerodynamically. It fulfilled its purpose, however, the three units installed averaging 100 per cent. recovery under all sorts of conditions during the six hundred hours of actual flying prior to the loss of the ship. A recovery of 110 per cent. was attained in flight on a number of occasions, sometimes for prolonged periods. The highest recovery attained was 130 per cent. on the ground, and under very favourable conditions. The complete installation (three units) weighed 1,350 lbs., for engines developing 900 horse-power; its resistance caused a reduction in speed of one knot at 45 knots.

This resistance, of course, represented a considerable loss of power, and experiments were initiated, even before the completion of the first project, aiming at its material reduction. The basis of the second design was the utilisation of the outer surface of the ship for the dissipation of heat. Larger heat transferring surfaces were necessary in this case, since turbulence conditions were less favourable than in a tubular condenser, and the velocity of the air over the surfaces was also less. It followed, therefore, that if the advantage gained from reduction in head resistance was not to be lost in increased weight, a material had to be found for the surfaces less in weight than aluminium. The use of fabric was decided upon, and tests were made to find a suitable material. That finally chosen survived an exposure to hot exhaust of more than 200 hours without appreciable deterioration. An experimental unit embodying this principle was installed on the Shenandoah and actually flown on the last few flights before the disaster, with results that were considered satisfactory. The apparatus was divided into two stages, the first stage consisting of aluminium tubes in which

the temperature was reduced from 1600°F. to about 150°F., and the second, of shallow fabric chambers, the outer walls of which replaced the outer cover. It was in these chambers that the actual condensation took place. As compared with the earlier type, the weight was reduced by 50 per cent. and the resistance by 75 per cent.

Commander J. C. HUNSAKER: I am very happy to be here to hear about the excellent work being done by Colonel Richmond and his associates. It is a perfect example of the scientific method. It is high time scientific methods were tried, and sound organisation applied to the problem.

Mr. R. V. SOUTHWELL said: The information given in Colonel Richmond's paper is so detailed and so new—coming, as it were, "hot from the mint"—that I feel I want to go away and study it closely before I venture to comment on it. But there is one fact which stands out even at a first reading: it is, that the development of airships is now governed by a new spirit, a full appreciation of the necessity for acquiring information vital to airship design by means of continued and systematic research.

In the war period our activities were mainly concerned with non-rigids, and non-rigids do not, I think, make such stringent demands for research. Take the question of shape. You may discover the ideally best shape for the envelope of an airship; but if that shape involves a fine tail, then although you can make your non-rigid envelope nominally to that shape, the tail is very likely to bend under the loads which come upon it, and you will have lost the efficiency you hoped to obtain. Similar remarks apply to the nose. You cannot be sure of its shape in practice, and Colonel Richmond has shown how sensitive the resistance is to quite small modifications in the shape of the nose, such as were made in R.33 when she was modified for mooring experiments. Or consider fin efficiency. In the non-rigid one is more or less obliged to put up with flat fins, attached to the envelope as best one can; in a rigid one can have fins of any shape in reason, and it becomes of the utmost importance to determine the shape which gives best efficiency. Again, for rigid airships strength is of course an utterly vital question; but in a non-rigid the tensile stresses imposed on the fabric by bending cannot exceed some definite limit imposed by the pressure of the contained gas. So for the rigid research is vital, and particularly full scale research, which demands special instruments of the kind described by Colonel Richmond. It is only recently that these have been produced, by the energy and inventive powers of the design staff at Cardington.

Until 1921, the technical details of full scale research were entrusted to members of the N.P.L., Mr. Pannell being in charge; and I well remember the sort of conditions under which he had to work. He would be informed at twelve o'clock on Saturday that a flight was starting from Howden on Sunday, and he was to go with such instruments as he could fit in the time. When he came back he would report that he had done his best to complete the experiment, but that the real purpose of the flight had been not research, but to give some member of Parliament a joy-ride over his constituency. It is surprising, I think, that so much full scale data was obtained under conditions of this kind; but the result of better conditions can be seen now, in the enormously increased output of data which has obtained since the new spirit came in.

I confess that I have never been able to forgive that total cessation of airship research in the years 1921-1924. It should never have happened. It is because of that cessation that Colonel Richmond and his staff have had to work at such high pressure now. As I have ventured to say elsewhere, we are witnessing the greatest adventure in constructional engineering which has happened in our time. Like all adventures, it calls for determination from those who are behind the front line; and my main point, which I am always trying to press, is the absolute necessity of maintaining continuity of policy behind the men who are doing the work. These men are obtaining their results with a

surprising rapidity. Let us hope that, whatever may be the policy with regard to building more ships when R.101 is in the air, at all events there may be absolute continuity on the research side, and then we can hope that knowledge will continue to increase as it has increased during the past year. Only so will airship design be put on a sound basis of exact knowledge.

Mr. J. D. NORTH: I have read Colonel Richmond's paper with great appreciation, and I most particularly admire the manner in which he has been able to accommodate so much new information in such a short period after the work has been carried out. His paper is a veritable stop-press edition.

Several speakers have emphasised the importance of systematic work and the necessity for determination to leave no stone unturned to carry this airship work to a successful conclusion. The whole history of engineering achievement has been one of success after many failures. The airship has been an instance in this respect. Reference is often made to the patient work and determination of the engineer, but too little attention is drawn to the patience and determination of those who are responsible for sponsoring the experiments but are not able to appreciate first-hand the technical position. Perseverance and determination on their part contributes quite as much to success as the work of the engineer.

The history of engineering achievement has frequently shown that the proverbial "haporth of tar" is found not to be available at the last moment or the completion of the work is expedited from considerations of policy. For these reasons in any engineering undertaking those who are responsible for the policy have a large share in the success or failure. In the case of the ships now under construction a broad-minded programme of research has been undertaken and nothing has been spared to make a success of the ship. A continuation of this policy through thick and thin, particularly through thin, will undoubtedly lead to ultimate success.

With regard to the last curve of girder construction which the lecturer shows, a 100 per cent. efficiency curve should be clearly understood to mean a 100 per cent. effective area and not to refer to the influence on efficiency of eccentricity, etc. It is also well to remember in looking at curves based on slenderness ratio that they are only a measure of efficiency provided the experimental members represented are appropriate to the structure. Thus a solid bar of metal plotted on such a basis would have 100 per cent. efficiency, but it is not, of course, suitable for aeronautical work.

Major G. H. SCOTT: I have been accused of being argumentative. I deny this accusation, and will prove that it is false by asking no questions.

As the probable future pilot of the airship, I should like to state my absolute confidence in the design of the new ship, the designer and his staff, and the very thorough way in which Colonel Richmond has tackled the 101 problems that come up in a new design of this sort.

Mr. W. E. GRAY: Regarding the question of knowledge of the extent of and the forces in bumps, it has occurred to me that it might be possible to get some data from accelerometer readings in heavier-than-air craft; it would probably require accurate measurements, and of the angles of the machines, but it might be just possible.

Air Vice-Marshal Sir W. S. BRANCKER: From what Air-Commodore Fellowes has told us, and from what we have heard to-night, I think we can congratulate ourselves that the design of this new ship is in extremely good hands. British airships have had a very troublous and unsatisfactory career in the past, but I feel that they have got a real chance now.

Finally, I would just call your attention to what the success of these airships may mean to the British Empire if our experimental service works all right. By the establishment of airship services radiating from London at sixty miles an hour cruising speed, which is less than that contemplated for R.101, we shall bring New Zealand to Somaliland, Australia to India, India to Egypt, South Africa to French Morocco, and Canada two-thirds of the way across the Atlantic.

It is for this reason that I feel that our airship development is probably the most important thing which is taking place in aviation to-day, and I will ask you to think at your leisure just what this would mean to the British Empire.

I know you will all join me in wishing Colonel Richmond success in his most important work and in what has been described as the greatest adventure in constructional engineering of our time. I thank him very heartily for a most excellent paper.

Colonel RICHMOND in reply to the discussion said: With regard to the all-metal airship, I would say that I admire brave and ingenious men, and I think that those who are building this airship are both. I do not think that an all-metal covering is an impossible proposition, and the day may come when we are confidently able to develop a large proportion of the strength of a rigid airship in the skin which covers the framework. At the present time, however, our knowledge on the distribution of stresses in a thin-walled shell of this type has not advanced very far, and I should be uneasy in relying on the shell to take any shear or compressive loads. If, on the other hand, the metal is being considered as a gastight material in place of the fabric, then it is a simple issue turning principally on the question of weight.

Referring to the recent pressure plotting experiments on R.33, Colonel Richmond said that no attempt was made to measure the effects of gusts as the object of the experiments was to obtain a comparison with wind tunnel results, which could only be carried out of course under steady conditions of air flow. Instruments were being developed, however, in which it was hoped ultimately to measure the actual strains in the girders under such disturbed conditions.

Group Captain Fellowes and Major Scott, he said, had neither of them pointed out the real advantage to the designer of having the pilot of the ship close at hand for regular consultation. Agreement having been obtained with the pilot at each step in the work, it follows that he will not be able to blame the designer, as is so often the case, if there are things in the ship which he does not like when it comes to fly.

With regard to Mr. Parker's remarks, the lecturer said that he had followed the work which had been done in America on water recovery with great interest, realising that this was a very vital matter in a helium-filled airship. He mentioned that experiments on water recovery gear for use in R.101 were in hand, and stated that the problem was rather more difficult in view of the fact that heavy oil semi-Diesel engines were being used, the exhaust of which contained much soot and excess air.

With regard to the question of corrosion raised by Mr. Parker, Colonel Richmond said that the steel which was being used in contact with duralumin was stainless steel, and that the duralumin was being oxidised. Tests had been made which showed that the rate of corrosion with this combination was very slow indeed.

Colonel Richmond said that he much appreciated the remarks which had been made by Commander Hunsaker, and that he had found inspiration in the thorough and painstaking way in which the airship problem was being tackled in America.

In connection with Mr. Southwell's remarks, he wished to emphasise how much he relied on the excellent advice and assistance which had been given by members of the National Physical Laboratory.

Replying to Mr. North's comments, Colonel Richmond said that he hoped he had made it quite clear that in discussing the efficiency of structural members it was no use taking some isolated member and comparing it with the efficiency of a member in a different structure. The member must be considered in relation to the whole structure in which a harmonious scheme had been followed.

The lecturer thanked Mr. Gray for his suggestion that aeroplanes should be used to determine the acceleration of the air occurring in gusts, but said that even if this information were available it would be very difficult to determine by calculation the forces imposed on the airship by a specified gust in free flight.

WILBUR WRIGHT MEMORIAL LECTURE

MAY 27TH, 1926

The President of the Society, Sir SEFTON BRANCKER, in introducing Mr. Lanchester, said: Before settling down to the real business of the afternoon, the delivery of the Wilbur Wright Memorial Lecture, I have an interesting and very pleasant duty to perform, the presentation of the Gold Medal of the Royal Aeronautical Society.

This is the highest honour that the Society can confer, and therefore the highest honour in the world which is awarded for accomplishment in aeronautical science. The Gold Medal has been previously awarded to only five persons, Orville and Wilbur Wright in May, 1909; Octave Chanute in July, 1910; Professor Bryan and Mr. Busk in May, 1915.

It is a very pleasant duty I have to perform to-night. When, in January last, the Council decided to award their Gold Medal to Professor Lanchester, the decision was taken unanimously.

I am not competent to speak fully of Professor Lanchester's great accomplishments. His work soars so far above my head that I cannot do him justice, but I do know that in all his theoretical work he has had a practical end in view, and his work, indeed, has resulted in great practical benefit to the men who fly.

I believe that one of Professor Lanchester's most important papers was that presented to the Society in 1897 on the circulation theory of lift, a theory he put forward as a result of the study of the work of various artillerists who, since 1761, had been investigating the flight of projectiles and the results of imparting a spin to shells and bullets. This paper was criticised and not accepted. Professor Lanchester was also the first to consider the end effect of wings of finite span, by means of vortices trailing from the wing tips.

No prophet is honoured in his own country, and we may well be ashamed that British scientists did not follow up his work with vigour and appreciation. Jakowski and Prandtl, however, made full use of his work. Prandtl began in 1910 and by the end of the war had established Lanchester's vortex theory by practical experiment and made it applicable as part of his routine of wing design.

Professor Lanchester's great scientific ability and accomplishments have now received world-wide recognition, and I am certain that the award of the sixth Gold Medal of the Society to him will be universally approved.

Some of you may remember that Professor Lanchester presided at the meeting of the Society in 1915 at which the last Gold Medal was presented, and that on this occasion also the Wilbur Wright Memorial Lecture was read.

The Wright brothers need no praise from me. Their courage, energy and enterprise are written large on the pages of history. Wilbur Wright was born in 1867. He and his brother Orville started to study the problems of flight in 1896. Among other pioneers whose records helped them in their early investigations was Stringfellow, a founder member of the Society. Twenty-two and a half years ago, on December 17th, 1903, the brothers Wright made their first flight on a power-driven aeroplane, an event which may well prove to be of almost unparalleled importance in the advance of civilisation.

Orville Wright is alive and well, and still working hard at Dayton, Ohio. I am proud to say that I can claim him as a friend, and I had a long talk with him only last March. Wilbur Wright died on May 30th, 1912, at the

early age of 45, too soon to see the results of his pioneer work. In commemoration of this sad event, and of his great legacy to the human race, the reading of the lecture was inaugurated.

Mr. F. W. LANCHESTER: As one of those present when the Wright brothers' machine was first flown in Europe, namely, at le Mans in 1908, it has been suggested to me that my recollections and first-hand investigations and observations might form an appropriate basis for the present lecture. It is a fact, however, that soon after my return from France—after investigating all that was then being accomplished, including visits to the works of MM. Voisin, Antoinette and others, and witnessing flights by Mr. Wilbur Wright at le Mans and M. Farman at Chalons—I had the honour of reading a paper before this Society entitled "The Wright and Voisin Types of Flying Machines—a Comparison" (December 8th, 1908), which very completely covered the ground.* I have re-examined this paper quite recently, and in spite of the difficulties experienced in obtaining information, there is practically nothing that I could add even in the light of modern knowledge, and equally nothing I should wish to modify.

As concerns the difficulty of obtaining information, I remember finding Mr. Wilbur Wright very indisposed to discuss either the technical aspects of his machine or more generally the problem or problems of mechanical flight. My own notes and criticism on which I afterwards founded my paper were submitted to him at le Mans, but his only comment was that the bird that talked most (the parrot) was a bad flier—witty, but not helpful! I sent him later a copy of the paper inviting his comments. Here is his reply in facsimile:—

Hotel du Dauphin,
Place de la Republique,
Le Mans.

Le Mans, 4 Jan 09,

Mr F.W. Lanchester.

Dear Sir,

I have your letter of 24 December and the copy of the paper containing the lecture to which you refer.

In glancing over the address I note such differences in matters of information, theory, and even ideals, as to make it quite out of the question to reach common ground by mere talk, as I think it will save me much time if I follow my usual plan, and let the truth make itself apparent in actual practice.

Yours very truly
Wilbur Wright.

The particulars given of the Wright aeroplane in my 1908 paper were consequently not as authentic as those relating to that of M. Voisin.

With the above as preface, the subject chosen for the present lecture is:—

* THE AERONAUTICAL JOURNAL, Vol. XIII., No. 49.

SUSTENTATION IN FLIGHT

The foundation of the modern theory of sustentation is the recognition of a cyclic or circulation component in the fluid motion surrounding the aerofoil.

But the "circulation" is of a somewhat abstract character. To the non-mathematical, and more generally to those who like to be positively assured that they are dealing with physical realities, the truth of the "circulation" is not altogether easy to demonstrate; in fact, it must be admitted that the word is used in a special sense.

Thus, when we talk of circulation we naturally expect to be able to track a particle in its path till it returns to some starting point or datum; such, for instance, as the underground trains on the inner circle, or as in the circulation of the blood from the heart through arteries, capillaries and veins, etc., and its return to the heart. Likewise in the case of the current on an electric circuit or the water in a hydraulic transmission system; we recognise the characteristic of circulation whether we are able to keep track of the actual particles or not.

But there is no circulation in this sense around an aerofoil; taking the aerofoil as datum or fixed (as in a wind channel), the particles of air approach from a distance, pass under or over the aerofoil, and away, without any suggestion of anything which in ordinary parlance is recognisable as "circulation."

To understand the meaning of circulation in connection with the aerofoil, it is necessary to dip lightly (fortunately very lightly) into hydrodynamic theory. It is established that any motion that can be generated in an inviscid fluid by forces applied by its boundary surfaces is irrotational, that is to say, the fluid particles cannot be given a spin, *i.e.*, caused to rotate. Moreover, in fluid without rotation the sum of the *circulation* on its boundary surfaces must be zero. This defines the special meaning of circulation with which we are concerned.

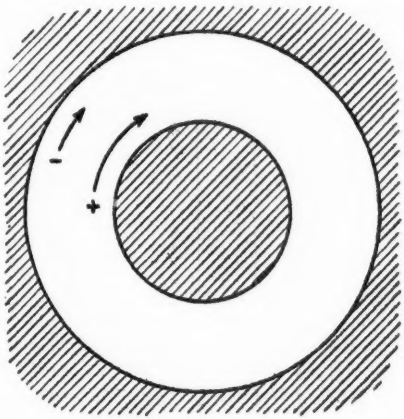


FIG. 1.

To fix our ideas let us take a simple case of two-dimensional motion in which the fluid is enclosed between an inner and outer concentric cylindrical boundary. Let the fluid be set in circulation (in the ordinary sense of the word) in the direction shown by the arrows. The region is one which is known as "doubly connected," * and provided the motion of the fluid be irrotational, the sum of the circulation on its inner and outer boundaries is zero.

* In a doubly connected region it is possible to describe a path which cannot be closed on to itself. In two-dimensional motion a doubly connected region has two boundaries; likewise with multiply connected regions, in two dimensions an n-ply connected region has n boundaries.

The *circulation* in its special sense is a boundary phenomenon and the circulation is measured by the velocity of the fluid along the boundary multiplied by the length of the boundary; circulation is an algebraic quantity measured plus or minus according to whether the boundary be on the right or left of a swimmer moving with the current. Thus if the circulation on the inner boundary be plus, that on the outer boundary will be minus. Although the circulation is defined by what takes place at the boundary, nevertheless given boundary conditions imply a definite motion within the fluid.

I am now endeavouring to explain, not to prove or to demonstrate. I will go through a few "exercises" with the system figured.

(1) In order that the motion of the fluid shall be irrotational, the velocity along the outer boundary must be less than that along the inner boundary in inverse proportion to the respective boundary lengths. As figured, this ratio is 2 : 1 and the lengths of the arrows indicate the respective velocities.

(2) As described in (1) the motion within the fluid is known as cyclic motion, and such motion requires a doubly (or multiply) connected region, *i.e.*, in a two-dimensional region, one in which the boundary itself is dual or multiple.

(3) We may suppose the outer boundary extended indefinitely in size or the inner boundary reduced to infinitesimal dimensions. And the form of the boundaries need not be circular, but in this latter case the boundary velocity is not uniform and the circulation requires integration for its evaluation.

(4) If the space within the inner boundary or "core" be supposed filled with fluid in rotation the system becomes a vortex.*

Now take the transverse section of an aerofoil as the inner boundary with its associated streamlines as in flight. The boundary streams above and below

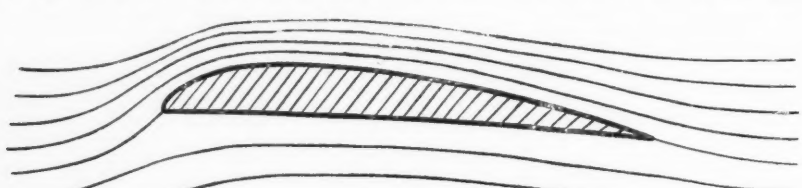


FIG. 2.

are opposed in sense, but the stream above is of higher velocity than that below, and an integration round the whole periphery of the section shows there to be circulation in a clockwise sense (in the diagram). *That is the circulation around the aerofoil.* The outer boundary has gone, we may say, to a distance indefinitely remote, but the equal and opposite circulation is nevertheless there, and the motion of the air occupying the whole region surrounding the aerofoil is irrotational and includes a cyclic component.

In leading off with the discussion of the subject of circulation and cyclic motion I am behaving like the man who dips into a novel at one of the middle chapters and afterwards turns to the beginning and reads it through. I propose now to start at the very beginning and deal in the most elementary manner possible with the simplest rudiments and historical development of the subject, believing that the foregoing discussion will save a later digression.

* The ideal condition is that the core is in uniform rotation, and that there is no discontinuity of motion between the core and the cyclic system at the boundary surface.

The early views as to the function of the aerofoil, or wings of a bird in the support of the load as apart from propulsion, were admittedly vague and unsatisfactory. Some of the early more serious attempts to deal with the problem consisted in a simple application of Newtonian principles as familiarised by Rankine's theory of propulsion. This theory has for its basis that in every second a certain mass of fluid, whether it be water or air, is operated upon by a propulsion mechanism, and has imparted to it a velocity. In the elementary case it is assumed that the velocity v so imparted is uniform over the whole mass, and consequently, knowing the mass m dealt with per second and the velocity v imparted, the momentum per second is known, and this momentum per second is a measure of the propulsive force W;

$$\left.\begin{array}{l} W = m\,v \text{ in absolute units} \\ \text{or } W = m\,v/32.2 \text{ (pounds)} \end{array}\right\} \quad . \quad . \quad . \quad (1)$$

The work done in propulsion is given by the expression

$$\text{Ft. lbs. per sec.} = m\,v^2/(2 \times 32.2) \quad . \quad . \quad . \quad (2)$$

By equating the two the result is obtained that the work done, or horse-power, for a given W varies inversely as the mass handled per second.

If W be varied the horse-power varies as W^2 the expression is:—

$$\text{Ft. lbs. per sec.} = 32.2\,W^2/2m \quad . \quad . \quad . \quad (3)$$

$$\text{Resistance (pounds)} = 32.2\,W^2/2\,m\,v \quad . \quad . \quad (4)$$

In the problem of propulsion the velocity is communicated to the mass in a rearward direction, and the force of propulsion, consequently, is forward. In applying this to the support of a load against gravity the mass handled is assumed to be projected in a downward direction, and the corresponding force, as calculated, is in an upward direction, *i.e.*, in support of the load. It is true that in actuality in the case of an aerofoil supporting a load the reaction has a backward component and consequently there is an additional expenditure of energy involved in dragging the mass of air dealt with forward; in other words, giving it a forward velocity as well as a downward one. But this fact is secondary, and may be left for subsequent consideration.

Now, whilst it is true that the Rankine theory of propulsion may be correctly applied in this manner, certain facts have to be taken into consideration which involve special interpretation of the theory but do not render it invalid. Thus the early attempts to explain sustentation in flight on the Rankine theory seemed to break down, and it was not until supplemented by other considerations, known to-day as the cyclic or circulation theory, and interpreted in the light thereof, that it was made effective. The nature of the discrepancy is as follows: If we take the trail angle of the plane or aerofoil as giving the downward velocity in terms of the velocity of flight, the mass required to give sustentation is too small to admit of the equation giving power expenditure being satisfied. Alternatively, if we take the mass great enough to balance the energy account, then the sustaining reaction becomes too great.

The trail angle is excessive and I am now trying to re-establish in our minds the position which existed before the introduction of the cyclic or circulation theory. It was natural, on encounterng the difficulties stated, to question the validity or applicability of the Rankine theory itself. Strictly speaking, the said theory is only true when the propulsion mechanism or supporting means, as the case may be, deals with matter in a discontinuous medium in which the particles do not react on one another as they do in a real fluid. Clearly a hypothesis so far removed from reality is open to suspicion and challenge. It was from this point that I myself started about the year 1891 in the endeavour to frame a rational treatment or theory which would account for the facts then known or believed to be known. I propose briefly to review the phases of argument which led eventually to the solution.

Taking first the case of the discontinuous medium and imagining an inclined plane to be drawn or propelled through same, colliding as it goes with a number of particles and flinging them downwards, thereby deriving sustentation, we see that the mean density of the medium will no longer be uniform; it will be increased in regions below the track of the plane. But in a medium possessed of continuity such as air this cannot happen; there may be a slight temporary compression of the air below and rarefaction above whilst the plane is passing, but there can be no permanent change of density or accumulation of matter in the lower strata of the atmosphere; the local down-current caused by the plane in its passage must find its counterpart in an up-current of equal displacement elsewhere. Superficially there may appear to be no difficulty in framing a régime to fulfil this condition; the down-current produced by the direct action of the plane or aerofoil is associated with up-currents generated beyond the wing tips. But this conclusion, which is in a sense the true solution, could not be accepted without closer examination, and it is not the whole story. Whatever tendency there may be to develop these up-currents beyond the wing tips, such tendency must also exist in front and in rear of the aerofoil, and in the case of an aerofoil of high aspect ratio, be far more powerful in these regions which provide "shorter cuts" from the pressure region below to the rarefaction region above. In order to investigate this aspect of the matter it was natural to take for examination the case of extreme aspect ratio, the limiting case in fact, an *aerofoil of infinite lateral extent*, one advantage of which is that it reduces the problem to motion in two dimensions. The solution is given in "Aerodynamics," pp. 149 *et seq.* The first step, leading ultimately to the cyclic or circulation theory, was to consider the case of a plane supporting a load without horizontal motion—a two-dimensional parachute. As the plane descends the air dragged down is compensated by an up-current round its edges. Now impart to the plane horizontal motion—the parachute becomes a glider—the question is what happens to the up-current.

We recognise that the circulatory motion of the air round the edges of the loaded plane are promoted by the difference of pressure between the under and upper surfaces. We can conceive a field of force everywhere defined by the initial acceleration of the air particles when the load is first applied. If there is initially no motion of the plane or aerofoil relatively to the air, the direction of the lines of force is everywhere defined by the initial movement of the particles. Then if a horizontal movement be impressed on the aerofoil we find that the streamlines in passing through this field of force will receive an upward acceleration as they approach the aerofoil and have an upward velocity when they encounter its leading edge. While passing under or over the aerofoil the field of force is in the opposite direction, viz., downwards, and thus the upward motion is converted into a downward motion. Then after the passage of the aerofoil the air is again in an upwardly directed field and the downward velocity imparted by the aerofoil is absorbed.

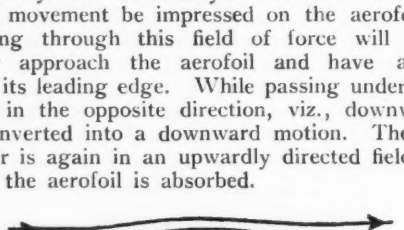


FIG. 4.

Now, since it is impossible for the residuary air to have a downward velocity (this would result in an accumulation or increase of density of the air below

the level of the aerofoil) it is necessary that the last state of the air shall be the same as its first state, viz., one of no motion. This result was immediately recognised as being most encouraging, in view of the fact that certain experimenters had found a lower resistance and higher lift factor in an aerofoil with a dipping front edge.* Further confirmation was found in the examination of the wings of birds which all show this feature to a greater or less extent. (Compare "Aerodynamics," § 108.)

The brief resumé given above is intended merely as an indication of the line of thought which led to the discovery of the cyclic system.† At the date of this investigation, 1892, I had very little acquaintance with classic hydrodynamic theory, or should have immediately recognised the form of fluid motion in question as a cyclic system superposed on a motion of translation, which identity was only recognised some three or four years later. One consequence of the system of motion depicted is that for an aerofoil of infinite span, or a finite aerofoil, travelling between two vertical walls or boundaries, the expenditure of energy (ignoring skin friction) is *nil*. At the time in question I regarded the system as a "forced wave," that is to say, a wave whose existence or maintenance depended upon a force (or distribution of forces) applied from without. This is a perfectly legitimate view, and in a patent specification (3608 of 1897) it is referred to as such, and the use of "capping planes" on the extremities of the aerofoil are described and figured "*in order to minimise the lateral dissipation of the supporting wave.*" The use of the capping planes is to simulate as far as possible the condition of an aerofoil operating in a region bounded by parallel walls, as in the ideal case of two-dimensional motion described. An analogous device has quite recently been adopted for the same reason in the form of a flange or shroud on the top of the rotors of the Rotor Ship, to which later reference will be made. Beyond the above publication, an account of the theory as it then stood was read before the Birmingham Natural History and Phil. Society in 1894; reproductions of wall diagrams then exhibited are given in "Aerodynamics," Figs. 61 to 68.

In view of the fact that a certain writer has stated that the theory was only a "success" when interpreted and extended recently by exact mathematical research it is perhaps legitimate to say that an actual aerofoil designed in the light of the theory and used in model gliders by me in 1894 when tested in the wind channels both at N.P.L. and Gottingen in 1912-13 gave a lift drag ratio exceeding 17 : 1, approximately 10 per cent. higher than any model up to that date tested.

One of the discouraging facts connected with the classic hydrodynamic theory—that is to say, the mathematical theory of the perfect fluid—is that the results appear superficially to have little resemblance to the actual motions experimentally ascertained for any real fluid with which we are acquainted, although there are analogies all along the line between electrical and magnetic fields and plottings from the hydrodynamic equations. This was early recognised and auxiliary hypotheses involving discontinuity were introduced to overcome the difficulty, notably by Kirchoff and Lord Rayleigh. But careful study reveals the fact that what is required more than anything else is interpretation. In brief, according to the classic theory all bodies in a perfect fluid behave as streamline bodies and experience no resistance whatever to their motion, likewise if a stream of fluid pass through a channel, however irregular its form and no matter what bends or corners the fluid has to negotiate, it experiences no obstruction. Moreover, the difference between the behaviour of the perfect fluid in these respects

* Horatio Phillips, who had observed this experimentally, gave an erroneous explanation in which the impact of the air on the dipping leading edge was supposed to throw the air up and so increase the suction effect, or more generally, the reaction on the aerofoil.

† A fuller exposé will be found in the Author's "Aerodynamics."

and the actual fluid is not to be accounted for by a direct effect of viscosity; the subject bristles with difficulties and subtleties which it is outside the scope of the present lecture to discuss. It is sufficient to state that hydrodynamic theory is like most other theory, its utility depends upon us recognising the conditions under which it is applicable and those under which it is not.

There are certain forms of body which in their motion through a fluid behave very much as the theory of the perfect fluid would indicate; such are commonly referred to as streamline bodies, such as fish-shaped or ichthyoid bodies. And the departure from theory in the case of such bodies can be in the main counted as direct effects of viscosity in which we include the phenomenon known as skin friction. The theory of ship resistance has been very largely founded on hydrodynamic theory in this respect.

Nevertheless, those concerned with problems in real hydrodynamics, or aerodynamics, which is the same thing, were not unnaturally slow to seek assistance from the hydrodynamic text book such as Lamb or Basset and it was thus that it was some three or four years before I was able to identify my "forced wave" with a cyclic-translational system. I will now proceed to show the precise meaning of this identity.

Let us take the simple case of the streamlines of a cyclic motion around a cylindrical bar or filament in a region without finite boundaries. Fig. 5 (diagram),

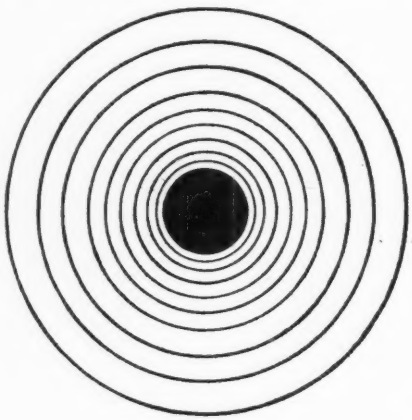


FIG. 5.

the bar or filament is supposed to extend to infinity so that the motion is two-dimensional and is thus fully represented in the diagram. The velocity of the stream is at every point inversely as its distance from the centre of the filament; this is shown by the width between adjacent streamlines. Now we superpose on this cyclic system a motion of translation. As given the motion of translation is horizontal, and in the same direction as the cyclic flow in the region above the filament, and in the opposite direction in the region below the filament; there will thus be some point below the filament at which the resultant motion is zero. Analysis shows that the resultant comprises two systems of flow, one external to a loop having its origin and termination at this point of zero motion and the other internal thereto; this as indicated in the Fig. 6a, full plotting being given in Fig. 6b.

In order that the whole combined system should be in equilibrium it is necessary that a downward force should be applied to the filament from without;

this may be otherwise expressed by saying that the filament experiences a supporting reaction.

Now if instead of a mere filament we substitute a cylindrical bar of considerable diameter the streamlines of the cyclic system remain much as before, but a certain position of the stream is cut out, but the circulation around the bar is the same as that round the filament which it has replaced. And when we

FIG. 6A.

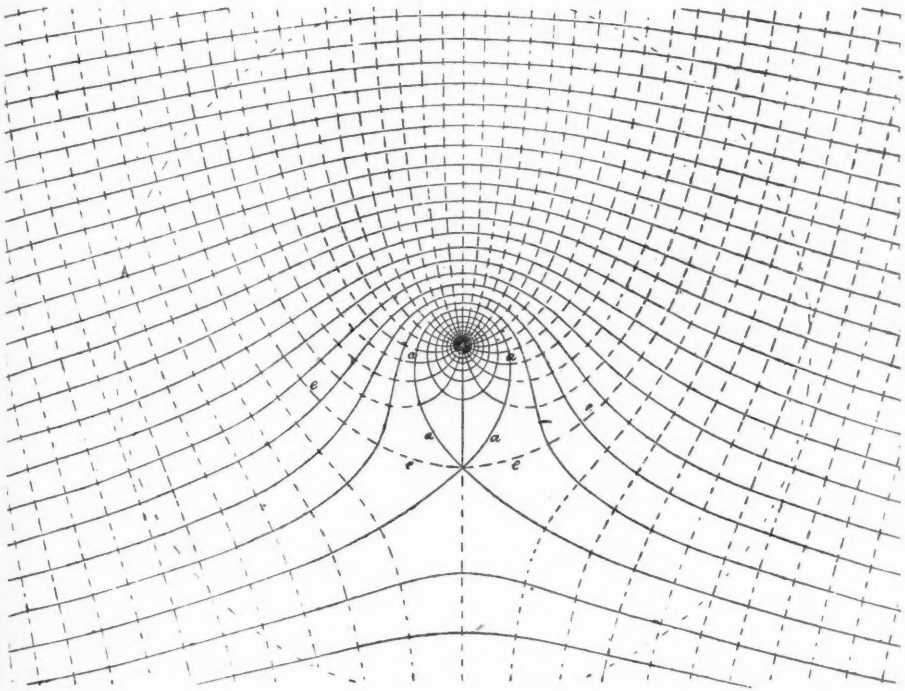


FIG. 6B.

compound with the cyclic system a motion of translation we have to take account of the size of the cylinder, that is to say, the translational system is no longer represented by rectilinear flow but by a system of streamlines representing the flow round a cyclinder (Fig. 8); the solution of this being perfectly well known, no difficulty in making an actual plotting is encountered. And if the (transla-

tional) stream velocity be chosen sufficiently high the internal system of flow disappears and the result is given in Fig. 7, a diagram only (not an actual plotting). Here we are able to see the manner in which the supporting reaction is generated, the higher velocity which denotes low pressure above the cylinder and the lower velocity which denotes higher pressure beneath. Moreover, we see the preponderance of flow round the surface of the cylinder in a clockwise sense which is the circulation (in the special sense) proper to the cyclic component of the system of flow on the inner boundary.

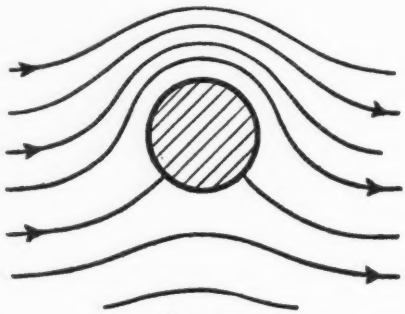


FIG. 7.

But now we have to take account of the difference between the real fluid and the perfect fluid of hydrodynamic theory. A circular cylinder is just as unsuited to functioning as a supporting member as it is to acting as a spar, in brief it has not the necessary streamline properties; in a real fluid such a section

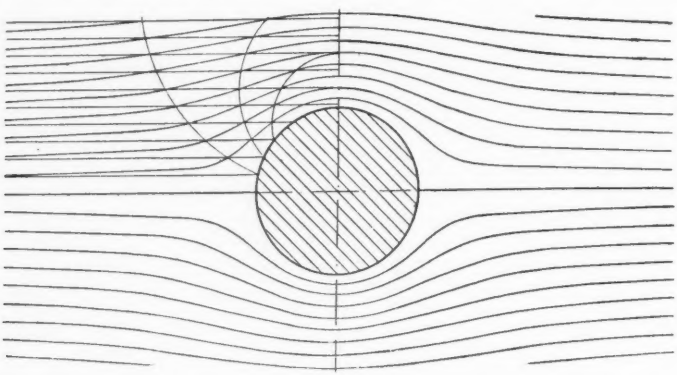


FIG. 8.

gives rise to incipient discontinuity and generates eddies or vortices. In my "Aerodynamics" solutions (plottings) are given of cyclic-translational flow round "cores" of other forms including planes in edgewise presentation both single (Fig. 9) and superposed (Fig. 10), an elliptic cyclinder (Fig. 11) and a plane in a region limited by a boundary surface (intended to represent the ground surface) (Fig. 12). None of these forms of "core" can be regarded as consistent with streamline motion. In the case of a plane, the stream in a real fluid would not conform to the streamlines of the equation in the region of the sharp turns either at leading or trailing edge; the leading edge would give rise to a surface of

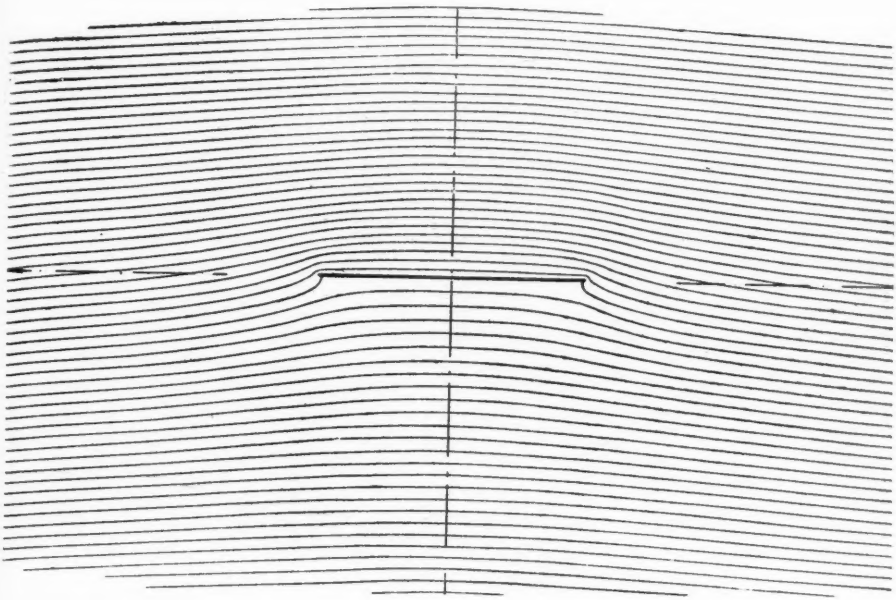


FIG. 9.

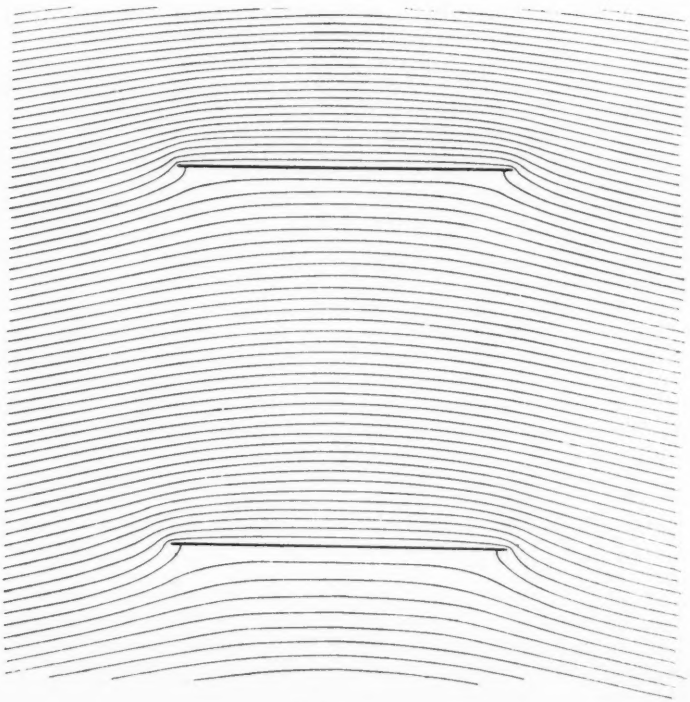


FIG. 10.

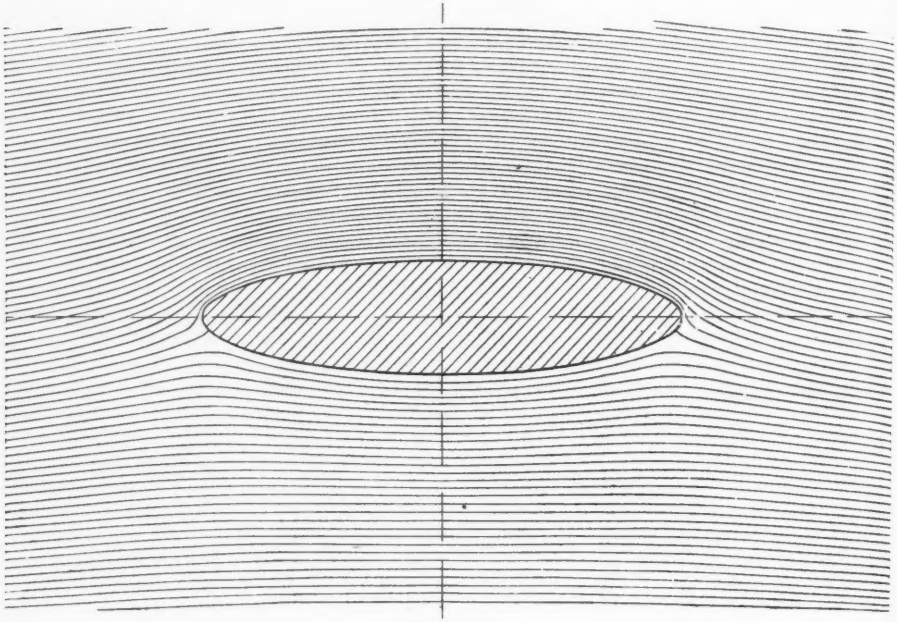


FIG. 11.

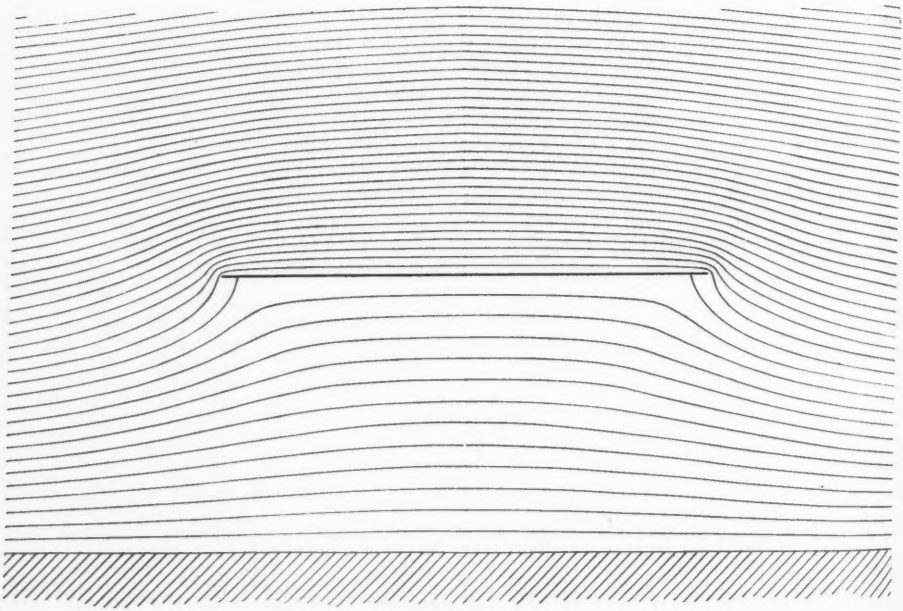


FIG. 12.

kinetic discontinuity or Helmholtz vortex sheet which immediately breaks up into a succession of vortex filaments, and the re-entrant stream at the trailing edge would be washed out, all as indicated in Fig. 13. The vortex motion generated by the leading edge represents a continual drain on the main cyclic system to which the support is due, and there would likewise be vortices emitted from the trailing edge owing to the difference of velocity between the upper and lower components of the wake stream where they unite.

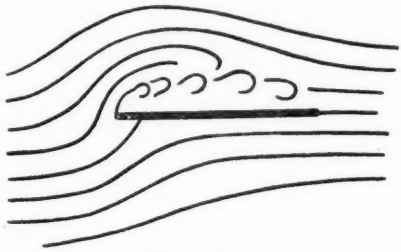


FIG. 13.

An elliptic cylinder would conform better to the requirements of streamline motion so far as entry is concerned, but the after part or " run " is too bluff and would give rise to vortices and degeneration. In the extreme case the elliptical cylinder approximates to a plane lamina. It is to be understood that there is no particular virtue in any of the forms of " core " above treated, whether circular cylinder, elliptic cylinder or plane except that the mathematical solutions and plotting are ready to hand; they are, nevertheless, quite useful for the purpose of study.

We appreciate the general character of the system of flow from these examples and realise its identity with that deduced from the argument already given based on a hypothetical field of force.

We are now in a position to face the three-dimensional conditions. In a qualitative sense the treatment of this aspect of the problem was dealt with in my original investigation, and a rather makeshift quantitative theory was built up on that basis in order to enable computations to be made of flight resistances and power expenditure for different values of aspect ratio. It was from this makeshift theory that my early experimental aerofoils were designed, and values were tabulated and finally published in " Aerodynamics." In spite of the paucity of experimental data, and the theoretical defects and apparent weaknesses in the theory, these tabulated results have turned out good forecasts.

I propose for the present purpose to ignore these early inconclusive efforts and pass at once to the more complete solution given in a paper read before the Institution of Automobile Engineers in March, 1915.* Time is short, the scene shifts. We take an aerofoil viewed in elevation along the line of flight (Fig. 14). As before, we consider sustentation primarily, leaving considerations of resistance to flight to be dealt with subsequently. What we see in the figure is the span of the aerofoil; along the span is distributed the load sustained. We want to know the form of the wake system when clear of the cyclic system to which we have so far devoted our attention. But a short digression is necessary.

When we deal with an aerofoil of finite span without the supposition of its being confined between parallel walls; that is to say, a finite span in an infinite or virtually infinite expanse of air, we have no longer to deal with a doubly connected region and consequently it might be supposed that there can be no cyclic motion. But we have seen that a vortex comprises a core containing

* Proceedings, Institution of Automobile Engineers, Volume IX, p. 169.

rotation and a cyclic system surrounding it, in brief a rotating mass of fluid can act as a bar or barrier to continuity and vortex cores are of the nature of " foreign bodies " which together with any rigid boundaries there may be determine the connectivity of the region. The cyclic system requires, therefore, that the aerofoil extremities shall be continued by vortices and that these vortices shall be generated by the aerofoil as to advances, also that the aggregate strength of each of these vortices as measured by their circulation shall be equal to the circulation around the aerofoil as due to the main cyclic system; this is as set forth at greater length in " Aerodynamics " and in the paper to which reference has been made.

We return now to Fig. 14. In the lower figure the two trailing vortices are figured diagrammatically by arrows indicating the motion in their respective cyclic systems, and this is the residuary motion left in the distant wake of the aerofoil. In the vicinity of the aerofoil we have the main cyclic system, which cannot be represented in the figure and which is carried along with the aerofoil

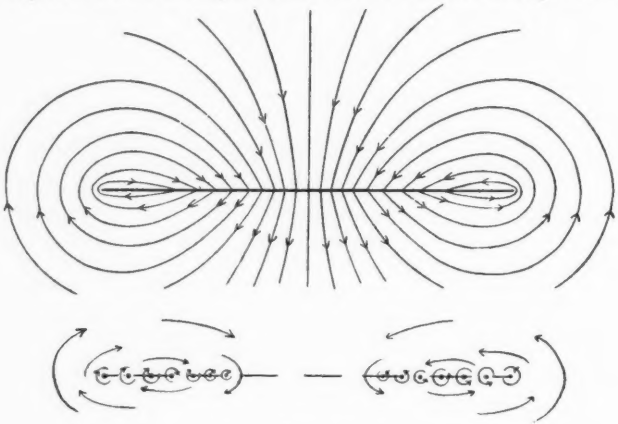


FIG. 14.

as a system whose energy is conserved. The vortex system, on the other hand, represents the work done dynamically in flight; its momentum is quantitatively counterpart to the supporting reaction, its energy is the measure of the energy dynamically expended. Since the essential condition for sustentation is that the momentum per second must equal the reaction if the weight sustained and the flight velocity are given, the momentum communicated in the formation of vortices per unit flight distance is known.

Now we may suppose the same form of motion to be given to the air by a distribution of forces over the total area acted on by the aerofoil simultaneously, instead of it being *spread* (if we may so express it) by the aerofoil itself. We have here to call in one of the devices well known to students of hydrodynamics, an imaginary surface forming a temporary barrier within the fluid to which an impulsive force distribution is applied. An impulsive force is one which acts for an infinitesimal period of time and is of correspondingly high order of magnitude. The measure of an impulse is momentum.

An impulse uniformly distributed over the area swept by the aerofoil results in a vortex pair in which the cores are of infinitesimal diameter surrounded by pure cyclic (irrotational) motion. Such a condition is impossible of fulfilment and if it were possible it would be undesirable, for the energy required to establish such a vortex pair would be higher than can be expressed in finite units. If we assume that the cores would actually be of measurable size the energy ceases to

be infinite, but the condition is clearly one not to be sought. What we have to achieve is to obtain the necessary reaction from the vortex system with the least expenditure of energy.

Now the mass represented by the individual flux streams differs for different positions along the span of the aerofoil, and we can treat these masses as though they constitute a real mass distribution on the Rankine-Newton theory. The mean downward velocity communicated is determined by the momentum to be imparted which is a measure of the load sustained and the energy is proportional to the mean square. It is a familiar theorem that the mean square is least (for a given mean) when the velocity is uniform, *i.e.*, the same for all increments of mass.

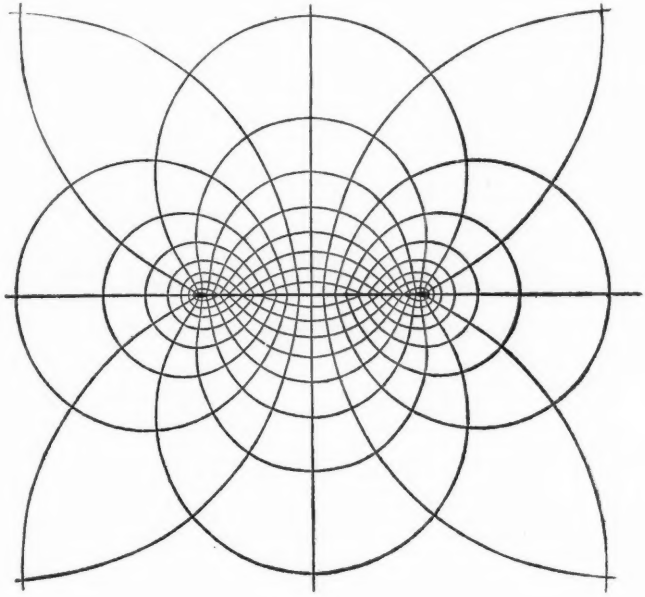


FIG. 15.

The solution (given in my 1915 paper) is therefore found in the streamlines of a rigid plane represented in section by the span to which an impulse is applied; the plane being imaginary it is supposed to dissolve after it has served its purpose leaving the resulting system of flow to "carry on." Such a plane gives an equal downward velocity over its whole surface (Fig. 15).

Now as to the mass equivalent of such a system. The rigid plane of the preceding paragraph may be taken as the extreme case of an elliptic cylinder, the aerofoil extremities of wing tips being the foci; as such its mass equivalent is given in "Aerodynamics," p. 110, and is equal to the fluid or air content of a circular cylinder whose diameter is equal to the aerofoil span, moreover the distribution of the reaction along the span is represented by the ordinates of the same cylinder. This is a result of the utmost value and importance.

The solution now given was not attained till some years after the publication of "Aerodynamics" (1907), but how nearly it was in sight can be gathered by reference to Fig. 83 and the passages on p. 176 of that work. This figure is reproduced in Fig. 14 and explains and shows correctly though not quantitatively the manner in which vortex sheets are produced by the lateral components of the

streamlines whose motion is outward beneath and inward above the aerofoil and how (as we were taught by Helmholtz) the vortex sheet being unstable breaks into a number of vortex filaments the cores of which contain air in rotation. The cyclic system of the individual vortices form part of a system in common, their filaments being carried round in the common system and wound together like the strands of a rope. Bit by bit, as the system degenerates, the rotation becomes less localised and the whole wake system may be regarded as a vortex pair in each limb of which rotation is distributed over a core of considerable cross section and in which there is no sharp demarkation between core and surrounding cyclic system.

We have now learnt to regard the origin of sustentation as derived from a cylinder of air whose diameter is equal to the span of the aerofoil, Fig. 16, at least to regard this as the ideal by which the most economical use may be made

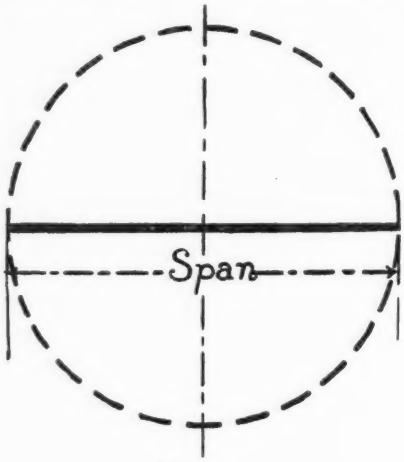


FIG. 16.

of a given span. In other words, we ignore the rest of the atmosphere and treat the dynamic problem on a purely Newtonian basis, the cylinder of air in question constituting the mass.

In order to achieve this particular condition it is evident that the aerofoil must be suitably graded as to its section at different points along its span. Fortunately it is not possible other than by sheer perversity to go very far wrong. That the conditions require a certain degree of wash out in the camber of the section towards the wing tips there is no doubt. It is also true that in most of the early machines this point was neglected. But even neglected the results were not so bad as might be expected; it may be borne in mind that anything approaching a square distribution is altogether impossible of fulfilment.

Fig. 16 gives plottings made from pitot tube analysis of a model (Advisory Committee Report, 1912-13, pp. 106-107); the different curves shown in the diagram relate to different angles of incidence. A quadrant is given and the scale of plotting is such that this shows the departure from the correct grading. Plottings as given for various angles of attack from 0 degrees to 8 degrees. It is clear that the camber of the aerofoil in question has insufficient wash out, also there is a curious kick-up near the region of the wing tips, which certainly is not conducive to economy. Obviously, by the analysis of aerofoils in this manner much may be done to effect improvement. It must be borne in mind, however, that sometimes economy is not all that is aimed at, the maximum load

for a given span, even at the sacrifice of economy, is sometimes the objective; and often it is a compromise that is required.

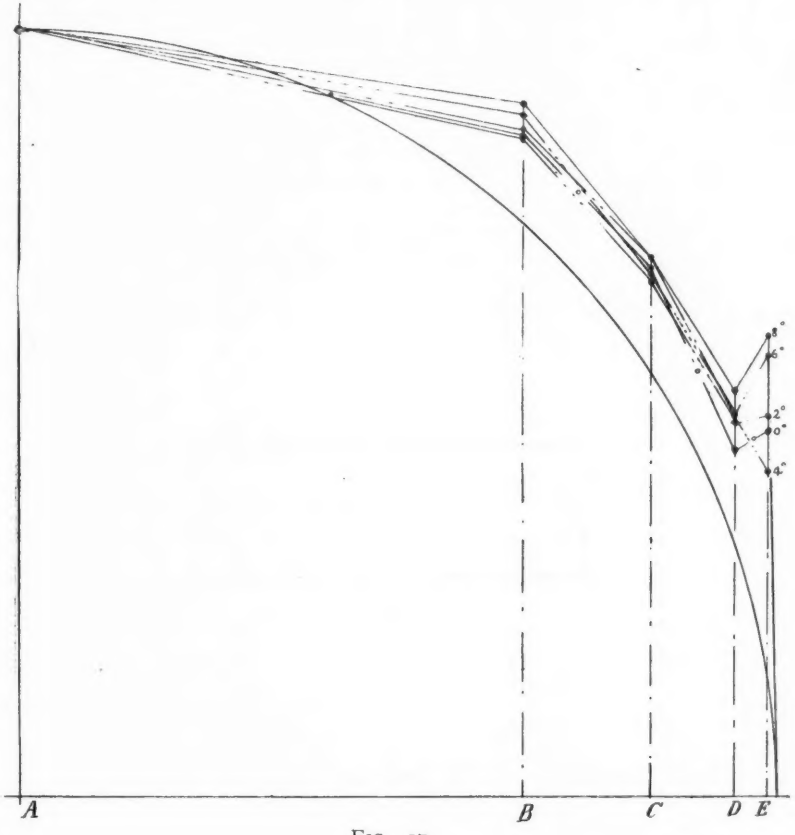


FIG. 17.

In order to illustrate the use that can be made of the cylindrical equivalent I have recalculated the aerodynamic resistance of the Wright and Voisin machines, for which I gave assessed values in my paper to this Society in 1908. The comparative results are as follows:—

	Old Estimate.	Present Computation.
Wright	60lbs. ...	55·5lbs.
Voisin	100lbs. ...	108lbs.

Considering all the possible sources of error, the results are reasonably concordant.

In the above calculation a difficulty arises in so much that the theory has only been developed fully as concerns the monoplane, whereas both machines are biplanes. This difficulty has been met by applying the approximation given in my 1915 paper, namely, to take the swept area as equal to that of a monoplane of the same span plus the rectangular area included between the planes, namely, span multiplied by the vertical distance of separation (Fig. 18). This approxi-

mation evidently is only good for small or moderate degrees of separation. An alternative is given in the paper to which reference has been made.

We now appreciate a fact that has been very slow of acceptance, namely, that the dynamic expenditure of power in flight (the power expended definitely in sustentation) is independent of the chord and wholly dependent upon the span. In one little detail this statement requires qualification and this qualification applies more particularly to aerofoils of very low aspect ratio. There is a certain extension of the span, that is to say, the effective span is greater than the actual span due to a spewing of the stream beyond the lateral extremities of the foil; in the case for example of a plane in apteroid aspect (*i.e.*, when the aspect ratio is less than unity) the Helmholtz vortex sheet spreads laterally some distance to

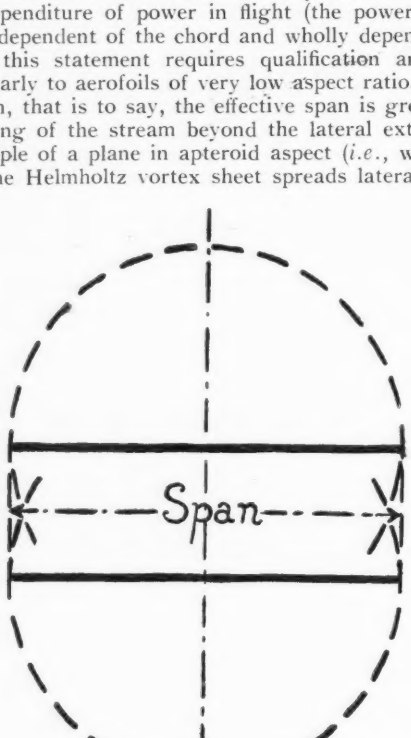


FIG. 18.

the right and left of the actual edges and consequently the vortex system has a greater base than the actual span. But under the conditions of actual design with aspect ratios such as can be usefully employed the statement can be taken as a fundamental truth.

The question instantly arises? What is the advantage of high aspect ratio? Why should a high aspect ratio give a better result than a low one? The answer is not far to seek. As the chord dimension is reduced, what the naval architect terms the " wetted surface " is diminished and skin friction becomes less. And what limits the extent to which the chord may be usefully reduced? A point is reached when, owing to the more violent camber and the thickness of section necessary to strength, a reduction of chord is not accompanied by a reduction of direct resistance; the coefficient of skin friction becomes augmented owing to increase in the mean velocity of the stream along the surfaces of the foil and the streamline regime begins to fail owing to formation of wake eddies. The conditions are analogous to those which limit the bluffness of section in a streamlined spar, there is a value at which the direct resistance is least. In my own

work I have followed the practice of naval architects initiated by Froude and assessed the direct resistance on the basis of an augmented coefficient.*

There is another entirely different aspect of the question as concerns the selection of aspect ratio. The range of flying speed is a matter of paramount importance; we require to associate a flight speed as high as economically attainable with the lowest landing speed possible. If we were to go to the extreme in the matter of economic design for some stated flight velocity and load and if that were all the problem the solution would not be open to doubt; but an aerofoil so constructed would have a very small range of available flight speed. The aspect ratio would be very high and a comparatively small change of the elevator would result in the shedding of vortices and loss of supporting reaction. When the angle of attack is varied, vortices are formed which carry away part of the main cyclic system and this gives rise to a loss of lift. A relatively low aspect ratio has been found best where a wide range of available flight speed is desired; the solution is in any case a compromise and is obtained by trial and error in the wind channel. It is a part of the art of the aeronautical designer to obtain the best possible compromise in each particular case with which he has to deal.

It is of interest to point out, when varying the chord, that although for a given span, carrying a given load at a given speed of flight, the energy dynamically expended is constant, compliance with the condition of least resistance means that as the chord is diminished and the direct resistance is reduced it pays to increase the span in order to maintain the relation *aerodynamic resistance* $=$ *direct resistance*, which is the condition of least total.

The justification for ignoring the drag component when considering sustentation is found in the fact that the forward component of the momentum communicated to the peripteral system is small compared to the vertical component. In the case of an aerofoil having a lift-drag ratio of 16, a figure that may be readily obtained and may be said to represent good practice, the aerodynamic drag (assuming the condition of least resistance) is $1/32$ of the weight sustained. This means that the forward velocity communicated to the equivalent mass of air handled is $1/32$ of the downward velocity and the energy unaccounted by the omission is $1/32^2$ of the total, or approximately $1/1000$th part. This, if thought worth while, may be added by way of correction.

The use of capping planes, *i.e.*, vertical planes in the line of flight fixed to mask the extremities of the aerofoil, was first suggested in my patent specification 3608 of 1897, and such planes act by hampering the escape of air round the ends of the aerofoil and so in effect increase the equivalent mass of the air handled. The value of this increase may be assessed as an area approximately equal to the span multiplied by the vertical dimension of the capping plane; this is not to be considered a rigorously exact statement but rather an indication of the magnitude of the effect to be expected. It means that aerodynamically a monoplane with capping planes is roughly equivalent to a biplane where the height of the capping planes in the one is equal to the distance of separation in the other. As far as I am aware, the use of capping planes has never been carried beyond the experimental stage, but their use is undoubtedly indicated where for any reason it is desired to make the most of a limited span, whether the limitation be due to reasons of easy stowage or transport.

Comment has been passed on the fact that a circular cylinder, although permitting of the ready plotting of the streamlines, is not of suitable section to form the aerofoil of a flying machine owing to its giving rise to eddies and excessive direct resistance; it is, moreover, not possible to make use of such a section in the ordinary manner since a circular section has no directional grip of the air such as necessary to enable the cyclic peripteral system to be established. But when the cylinder is given rotation about its axis the conditions become

* The Flying Machine from an Engineering Standpoint. Lanchester, Constable and Co., 1918. Appendix I.

totally different; there is no doubt that if any circumstances should be found to make it worth while, a flying machine could be constructed with rotating cylindrical wings as in the analogous use of the same device in the rotor ship. It is well understood that the action of a ship's sails is strictly analogous to that of an aerofoil. The sails of a ship are in fact aerofoils giving rise to a cyclic system and subject to the same considerations and laws, the sail is one method of developing a cyclic system, the rotor is another. It is of interest to note that the use of capping planes in the form of circular discs or " shrouds " at the top of the rotors has come into vogue, this innovation being due, I understand, to Prof. Prandtl. It is of interest to trace the precise means by which the rotor gives rise to the cyclic-vortex system. The problem was discussed to some extent in connection with the behaviour of a ball having " cut " or spin in its flight (" Aerodynamics," p. 43) from which Fig. 19 is reproduced. It is clear

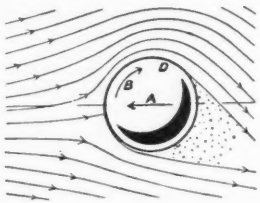


FIG. 19.

that the rotating body, whether it be a ball or a cylinder, cannot by its spin communicate a circulatory movement to the deeper layers of the air *directly*; its direct action, so far as distinguished from a body not in rotation is concerned, is confined to the layer of air sweeping its surface involved in the phenomenon of skin friction; this we know is quite a thin film. But this layer acting on the air adjacent to it causes a deflection of the wake stream; in brief, what is known as the dead water is pumped out on the one side and pumped in, forcing the stream away, on the other. This action engenders a lateral reaction which results in a field of force which acts, just as already described in the case of the aerofoil, on the deeper seated layers of the air and so sets up the cyclic system. Thus, the action is cumulative; from the small skin-frictional beginning, increment by increment the whole cyclic vortex system is developed. Without an explanation such as the above it would be impossible to account for the unsymmetrical disturbance of the air *in advance of* the rotor which is an essential part of the phenomenon.

Another application of the circulation or cyclic theory is to be found in the sustentation of skimmer-craft or so-called hydroplanes; here the peripteral area is a semi-circle whose diameter is the length of the " step." The system is similar to that concerned in the support of an aerofoil, but the upper half is missing.

In the present lecture I have endeavoured to give a connected account of the modern theory of sustentation. I have stated the theory as I see it, in plain English divested of all mathematical ornament, and, it is necessary to add, taking for granted a great deal in the way of mathematical substructure. I have given the theory as I have developed it and have made no more than an occasional reference to the work of others; there are many others who have worked in the same field and contributed much to the present-day knowledge of the subject. Some of my own results may have been anticipated by other workers. I am informed that it is so. If it were ever worth doing, it would probably take a trained investigator some years to go through all the literature of the subject and rightly allot to each worker his share of credit. It is a task for the technical historian of the future; I am content to leave it in his hands.

STUDENTS' PAPERS

BERNOULLI'S THEOREM IN AERODYNAMICS

Paper read on Thursday, February 18th, at 6 p.m., in the Library, at 7, Albemarle Street, London, W.1.

BY M. S. HOOPER.

Students of Nature have come to believe that the sum total of energy cannot be changed; that is, in the principle of the conservation of energy. Bernoulli's theorem is a simple expression of the application of the principle to fluid motion and in this form the principle is probably one of the most useful conceptions that the engineer has as a guide in a subject which presents many difficult problems.

Daniel Bernoulli, born in the first year of the eighteenth century, published his chief work, "Hydrodynamics," in 1738. Among the results of his researches collected therein is the theorem now known by his name. Long before Bernoulli's time men had been concerned with fluid motion. It has been suggested that in ancient Rome the principle of the venturi tube was used, if not understood, to evade water rates.

Equation (3) below expressed the conservation of energy, neglecting changes of potential energy due to variations of altitude following deflection. Or the theorem may be proved directly, without accepting the principle, as follows:—

Considering the motion of a small cylinder of fluid of section a and density ρ, with its axis of length δs along a streamline if V be the velocity and S the component of external force per unit mass in the direction of the streamline, then, equating the product of mass and acceleration of the small cylinder to the other forces acting,

$$\rho a \delta s \, (DV/Dt) = \rho a \delta s S - a \, (\partial p/\partial s) \, \delta s.$$

Now

$$DV/Dt = \partial V/\partial t + V \, (\partial V/\partial s),$$

so that

$$\partial V/\partial t + V \, (\partial V/\partial s) = S - (1/\rho) \, (\partial p/\partial s) \quad . \quad . \quad . \quad . \quad (1)$$

If the motion be steady $\partial V/\partial t = 0$, and if the external forces have a potential function such that $S = -\partial F/\partial s$, then by integrating along a streamline,

$$\int dp/p + \tfrac{1}{2}V^2 + F = C \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where C is a constant, whose value depends on the streamline chosen.

This general form of Bernoulli's theorem may be simplified for use in aerodynamics. F is an external force (gravity in problems of aerodynamics) and may be neglected. A fluid exists either as a liquid or as a gas. This distinction does not matter so long as compressibility does not play a part, which can be shown to be true below velocities which are only reached in aerodynamics near the tips of airscrew blades. Thus ρ may be considered constant and we obtain the convenient form

$$p + \tfrac{1}{2}\rho V^2 = C \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where p is the static pressure—inversely proportional, it is seen, to V^2.

No account is taken in the above of effects due to viscosity, which would be represented by tangential tractions along the sides of the cylinder reducing the resulting force. Thus the result is only an approximate expression because all real fluids have this property.

There are many cases of flow in which the theorem is useless. For instance, below a certain limit of the product of velocity and diameter divided by the kinematic viscosity the flow of a real fluid through a circular pipe is streamline and may be calculated in detail, there being no eddies. With a given pipe and fluid at higher speeds eddies are formed which cause resistance along the pipe to vary much more nearly as the square of the speed instead of as the first power. In neither case does Bernoulli's theorem hold; in fact, the first case is the most useful method of determining the viscosity of a fluid. Hence Bernoulli's equation does not rigidly hold through a venturi tube, but owing to the short length a corrective factor is found to be sufficient. In terms of energy, the loss along the limited portion of the pipe is too small to affect to a serious extent the large changes in pressure and velocity caused by the local contraction of the stream.

In this way there arise several sets of conditions of flow in real fluids under which the equation may be applied with considerable accuracy and in these cases its use is to give the simple relation between pressure and velocity. The most familiar illustration is the measurement of the velocity of a stream by means of a pitot-static pressure head. When the axis of the tube lies along a streamline the velocity falls from V to o in the pitot tube, so that a manometer connected to a pitot tube indicates the value of $p+\frac{1}{2}\rho V^2$ in the neighbourhood of the mouth of the tube. Almost any shape of tube will give this, the only difficulty in the development of the now conventional N.P.L. form of pitot-static pressure head being the necessity to ensure that the pressure in the static tube is the " atmospheric " pressure in the fluid. This step is required to make the theorem available for the finding of velocity.

When a pipe is considered as a whole a phenomenon of great importance is found. In the mouth of the pipe is a region of fluid throughout which Bernoulli's equation holds very closely, except close to the walls. As Osborne Reynolds pointed out and Dr. Stanton has confirmed, no increase in the speed makes turbulence begin at the mouth of the pipe. Professor Bairstow has suggested that the turbulence which ultimately shows itself throughout the pipe is propagated radially from the sides, the shear that starts at the mouth of the pipe taking time to travel to the centre. The phenomenon in the mouth of a pipe is utilised in the case of the wind channel. The design of a channel is such that changes in the air, due to the resistance of the walls, do not extend more than a few inches into the stream at the section used for experiments and consequently do not affect the model. It should be possible to measure the velocity in the channel from the static pressure there compared with the atmospheric pressure, but this is not possible because of the loss of energy at the mouth of a practical type of channel.

A standard application of the equation is made in drawing office calculations for airscrew design. Viscous effects are neglected and it is assumed that the only change in the energy of the fluid occurs at the propeller disc. The simple form of Bernoulli's equation is applied to the two parts of the average streamlines which are separated by the propeller disc. Justification for this use of the equation lies ultimately in the excellence of the final results. The total thrust found from thrust-grading diagrams obtained experimentally by means of the pitot tube is in close agreement, however, with the result obtained by direct measurement and provides an exceptionally interesting illustration of the use of the theorem.

Except in the slipstream the form of the equation is $p+\frac{1}{2}\rho V^2=C$. Within the slipstream at a given distance from the airscrew, at radii r_1, r_2, r_3, etc., C has the values C_1, C_2, C_3, etc., because the energy imparted to the fluid is different from one streamline to the next.

The application of Bernoulli's theorem to wing flow is very extensive. It

lies at the heart of Prandtl's theory of aerofoils which has become so important a part of aerodynamics. On the experimental side, some years ago, it was shown that as an aerofoil is approached from above the pitot head—that is, $p + \frac{1}{2}\rho V^2$—varies but little until a point near the surface of the aerofoil is reached, when the pitot head begins to drop very quickly. In fact, so rapid is the loss of head that the points where it starts to fall can be found easily by experiment. When plotted these points are found to lie on a surface—for a similar drop of head occurs, of course, near the underside—that surface or pitot boundary enveloping the aerofoil and trailing behind it. It has been likened to a bag attached to the aerofoil and extending back beyond the trailing edge, widening the distance downstream. The "bag" includes the cores at least of the wing-tip vortices and throughout the pitot head is diminished, so that the equation does not apply to this region. But experimental evidence exists to show that Bernoulli's theorem holds for well outside the cores in spite of circulation. The theorem is also seen to be nearly true in spite of great velocity changes and gradients except close to the surface.

The phenomenon of a "bag" occurs, of course, around every body moving in a fluid, the motion inside being turbulent at the scales common in aeronautics. It is a region in which the loss of energy is usually kinetic and one in which occurs at least a large part of the drag.

At East London College experiments have been made with an aerofoil whose section is fairly thick, somewhat like that of R.A.F. 19. The aerofoil is rectangular in plan form and uniform of section with square-ended wing tips. Iso-pitot-loss curves were found for a section through the "bag," at right angles to the direction of undisturbed flow, one chord behind the trailing edge. These curves through points of equal pitot loss are given in Fig. 1 and show, in contour form, the deviation from the constant in Bernoulli's equation.

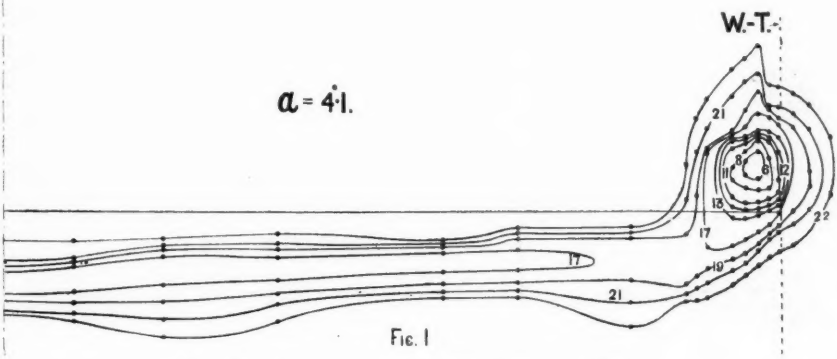


FIG. 1

Iso-pitot-loss curve. No.	Pitot loss $\div \rho V^2$.
22	−.005
21	+.008
19	.003
17	.083
13	.183
12	.233
11	.283
8	.383
6	.483

The downwash angle was measured in that experimental plane one chord behind the trailing edge. The angle of the stream was measured above, through and below the layer. The measurements showed that fluid poured down through the pitot boundary into the "bag," most of it remaining in that region of turbulence. In other words, the widening of the "bag" was nearly equal to the rate at which fluid was crossing into it.

To illustrate further the regions of the disturbed motion in which Bernoulli's equation ceases to apply the iso-pitot-loss curves have been found, at one value of Reynolds' number, behind a plate, cylinder and strut (see Fig. 2, 3 and 4). Each of the bodies stretched from side to side of the four-foot wind channel at East London College. The measurements were made in the middle of the

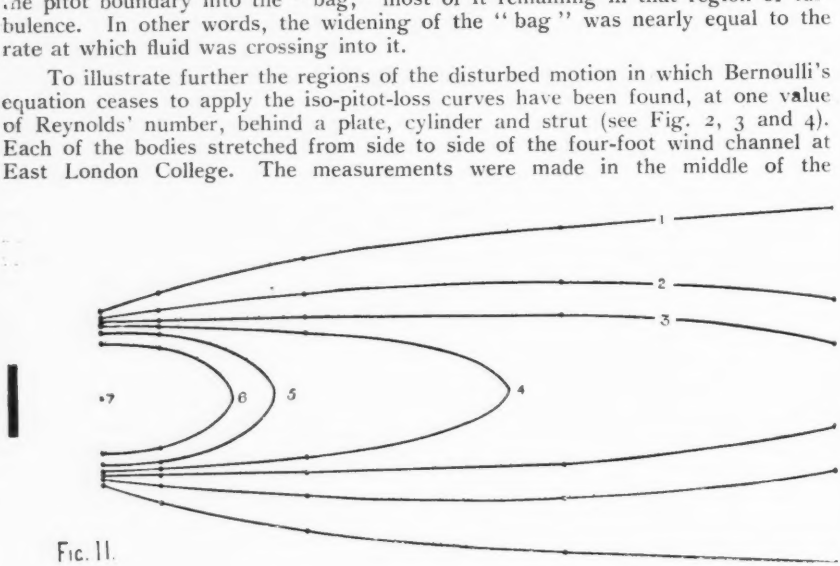


Fig. II.

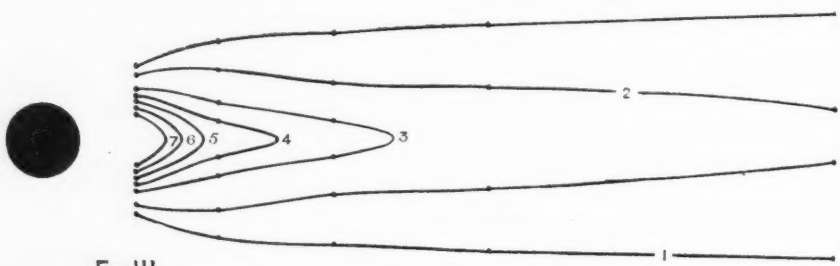


Fig. III

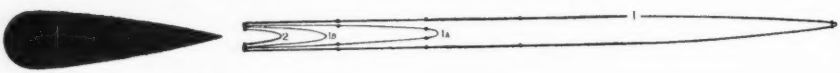


Fig. IV.

Iso-pitot-loss curve. No.	Pitot loss $\div \rho V^2$.
I	0.05
IA	0.10
IB	0.15
2	0.20
3	0.40
4	0.60
5	0.80
6	1.00
7	1.20

channel. Of course, it is known that the motion is very turbulent in the "bag" which trails behind, say, a cylinder. The arrangement of the vortices is, roughly, as follows:—A vortex, grown large, is about to leave the cylinder on one side. On the other side a vortex is forming, just beginning its career. That distribution of vortices alternates from one side to the other of the cylinder. It is a periodic phenomenon. But by means of a pitot tube, suitably oriented, connected to a tilting gauge, suitably damped, the average effect may be measured.

The pitot loss contours show how widespread is the disturbance behind the plate and the cylinder compared with that behind the strut. The contours show, further, differences in the "bags" behind the plate and cylinder, and when the static pressure is constant the contours form a picture of the distribution of the square of the speed. From photographic evidence it is known that the vortices are strong behind a cylinder and of much less strength behind a strut, whence it seems possible that large pitot losses, *i.e.*, large departures from Bernoulli's equation, are due to strong eddying. It may be, therefore, that these losses depend on the amount of eddying initially present in the undisturbed stream.

Some observations of interest follow from a study of the distribution of pitot loss. The "bags" belonging to supports for a model in the wind channel, for instance, interfere with the boundary layer essential to the model, thus making it necessary (as is well known) that these supports be small in order to avoid a fictitious value of k_D. Parts of the bag are only slightly stable, so that obstructions, about the size of an ordinary pitot tube, moved about in the stream may cause a displacement when the obstruction is not touching the body and hence may cause a change in k_L and k_D. Great care is thus sometimes called for when designing apparatus for measuring the motion.

A very large subject has been but lightly touched in the foregoing. It will serve a use if it has suggested that study in greater detail of the way in which Bernoulli's theorem may be used in fluid motion is more necessary to the aeronautical engineer than to the civil engineer. Whilst the civil engineer may, in some cases, regard departures from the theorem as rather a nuisance, in that they need corrective constants to be determined, such departures are of the essence of some problems common in aerodynamics.

Paper read on Thursday, March 25th, at 6.30 p.m., in the Library at 7, Albemarle Street, London, W.1.

STALLED FLYING

BY S. SCOTT HALL, B.SC., D.I.C.

Stalled flying is a subject which at the present time is occupying the thought and time of aerodynamic experts all over the world. It is still more or less in the experimental stages, but its value to flying, and more especially commercial aeronautics, is now almost universally recognised.

It has hitherto been possible to fly an aeroplane at all angles of incidence from the no-lift angle up to the burble point of the aerofoil section employed for the wings. The burble point on the lift curve marks the change-over from streamline to turbulent critical airflow, and at this angle the aeroplane will stall. The machine sinks, and what is more dangerous, becomes unstable laterally so that the pilot loses power over its orientation. A spin then usually ensues.

It may be as well to state here that the only way of defining the change-over point from normal to stalled conditions is by means of the stalling *angle*. The term stalling speed means next to nothing, because obviously if a machine is in a banked turn the speed at which stalling takes place will be higher than in steady straight flight owing to the additional component of the centrifugal force. Similarly, the speed is dependent on height.

There are two separate types of stall. The first, which is very rare indeed, is due to longitudinal instability, and gives rise to a sudden forward dive—quite distinct from the dive *following* a spin. The second form of stall, which is very common and responsible for quite two-thirds of the fatal air accidents up to date, is known as the incipient spin. Suppose that the machine is just stalling. The flow over the wings is very unstable. A slight gust pushes one wing up. The pilot endeavours to right the machine in the only way he knows, namely, by pushing the aileron down on the descending wing. This action does not increase the lift on the already stalled wing, and brings in a powerful negative yawing moment due to the drag of the aileron, which at the high angle of incidence is considerable. This yawing moment adds itself to a yawing moment in the same direction already induced by the roll, and the machine under combined yaw and roll starts into a spin. The only moment tending to oppose this is a very small yawing moment produced by the sideslip of the machine towards the falling wing tip.

To enable a pilot to avoid the incipient spin, should he stall his machine, he requires:—

1. Greater control in roll: that is, greater aileron control.
2. (*a*) Either greatly increased control in yaw: that is, increased rudder control; or
   (*b*) Some device whereby the adverse yawing moment due to aileron drag may be nullified or even reversed in sign to help counteract the yawing moment induced by the wings in rolling. This second method would leave the rudder the same size as required for normal steady flight.

The whole crux of the matter is the yawing moment. This fact was realised early in the investigations by Professor B. Melvill Jones, who has made a special study of this subject.

Efforts were made, therefore, to prove satisfactorily that if sufficient control

in yaw could be given, a pilot could fly stalled on a fairly still day when "bumpiness" was not too bad.

One of the principal experiments in this direction was the fitting of a standard Avro training machine with a rudder of about three times the normal area, giving what had been calculated to be the yawing moment required (see R. & M. 963). The methods used to arrive at these figures of moments necessary for adequate control are explained in Professor Jones's paper before the Society in 1923. It is sufficient to say that a necessary but not sufficient criterion of controllability is that of balance of the aeroplane about all three axes, and that for adequate control the power to produce the necessary accelerations is also required. Another fundamental feature used for the purpose of simplification was that of considering the moments and forces separately and neglecting the effects of one upon the others. This in most cases for a first approximation is sufficiently accurate.

The next step was the production of a device which would counteract or reverse the yawing moment without increasing the rudder area, which has obvious disadvantages from the point of view of extra weight of the rudder itself and also of the fuselage due to the necessity of extra strengthening.

One of the first efforts was known as Fage's device—a form of flap in the leading edge (R. & M. 855). Several other methods were suggested at the same time. Modifications to ailerons were also tried, such as the de Havilland differential gear causing the down-going aileron to move through a smaller angle than the up-going one. Balancing the ailerons aerodynamically was tried, also changes in their section.

A floating aileron suspended between the two wings was thought at one time to give a solution to the problem, but in practice was useless.

In 1920 Mr. Handley Page invented the slotted wing for giving increased lift to an otherwise normal section. These slots arranged along the leading edge of the planes give increased lift and slightly increased drag when opened, but when shut give the wing section practically normal characteristics. The Aeronautical Research Committee applied the idea of the increased lift due to the slots to the problem of lateral control, and suggested that a short length of slot operated in conjunction with an aileron might give the necessary reduction or reversed yawing moment.

This idea was tried in the wind tunnel first and the results there obtained by opening the slot at the maximum downward angle of the aileron, and closing it as the aileron ascended gave such promise that a full scale machine—again a standard Avro—was fitted with slots operating in conjunction with ailerons by means of a cam mechanism. The device was tested at Farnborough and an exhibition flight was given at Croydon Aerodrome. At normal angles of incidence the device gives much the same control as the simple aileron. At high angles of incidence beyond the stalling point the yawing moment associated with normal ailerons is reversed in sign or zero, whilst good control in roll is given. To quote actual figures, conventional ailerons on a stalled wing give a maximum moment coefficient of about 20. The slot and aileron control gives a moment coefficient of 35, and pushed to its extreme limit a coefficient of 60.

The moment coefficient used here is defined as:—

$$\text{Moment in lbs. ft.} \times 1{,}000/\rho V^2 S s$$

Where ρ is the air density,
V is the velocity of the aeroplane,
S is the wing area,
s is the semi-span of the wings.

The above figures are quoted from Professor Jones's paper. See also R. & M. 916 and R. & M. 968.

A further development of this device might conceivably be in slotting the ailerons themselves.

At the time of the demonstration at Croydon of the slot and aileron device an exhibition of the same nature was carried out by Fokker on a passenger-carrying monoplane fitted with normal control surfaces. Though perhaps not giving as spectacular a demonstration as the Avro machine, he quite definitely flew his machine stalled and under definite lateral control.

This brings one to a second category of factors which may have a very decided effect on the stall of a machine.

Let us assume for a start that we provide on our machine good control right down to the stall so that there is no lateral sloppiness of the controls at about 10-12 m.p.h. above this point—a failure of so many machines.

It would appear that one of the most important points to observe in the question of stalling is that of the wing tip loading. This is indicated by curves of lift distribution over the span.

Suppose that we taper the wing and give it an aerodynamic twist as well, decreasing the angle of incidence of the wing as we proceed out towards the tips. This will decrease the lift on the tips at normal angles of incidence and the aileron control will not be quite so good perhaps over this range. As, however, the central and main portion of the wing reaches and passes the stalling point, the tip sections are just approaching their maximum angle of lift, where the ailerons will exert their fullest power without the down-going one incurring any exceptional drag. See JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY, April, 1926, page 243.

Another aerodynamic feature that is believed to have some effect is the nature of the lift curve at the burble point. If this comes to a sharp bump as is the case with some sections—notably thick ones with no lower camber—and the fall of lift is very rapid, then a sudden sharp stall will result.

If on the other hand the curve is well rounded at the top and the decline slow, a slow stall may be expected, other features of the wing being the same in both cases.

Yet another characteristic which obviously has a great influence is the autorotation range of the machine. In this connection the biplane structure has a decided advantage over the monoplane, and the questions of gap, which should be as large as possible, and stagger are important. In general, thick sections with high curvature of the centre line are at a disadvantage with the thin low camber aerofoil.

The Lanchester-Prandtl theory shows that trailing from each tip of a normal wing in flight is a powerful vortex. One believes that research is being carried out now to investigate the possibility of designing a wing to eliminate these vortices by " washing-out " the tips of the wing much in the same manner that has been described. It is possible that this might alter the conditions existing at the wing tips at the stall and open another way to a solution.

In a paper of this kind it seems fitting to make some mention of stalled landings of the intentional variety. This problem seems to be one mainly of undercarriage design. It is obvious that an abnormally strong (and heavy) undercarriage and fuselage would have to be provided, and with the machine landing as it would, with its tail well down, the length of the undercarriage legs necessary would make the machine appear more like a daddy-longlegs than anything else.

A bird alighting performs a manœuvre which seems very like a stalled landing, and what is more, the wing tip feathers (seem to) open in a way curiously suggestive of slots. Perhaps this analogy is rather wide of the mark, but it is an interesting point nevertheless.

An endeavour has been made in this paper to give a general description of the phenomenon of stalling, of the mechanical methods which have been used up to date to give the pilot power to control when stalled, and lastly to indicate several other fundamental properties of a machine which may have a great bearing on the problem.

SUPERCHARGED AERO ENGINES

Paper read before a Students' Meeting on Thursday, April 15th, 1926, at 6.0 p.m.

BY R. F. R. PIERCE.

The main object of this paper is to show the importance of supercharging, the desirable results brought about by the process, and a consideration of the difficulties.

Supercharging, as understood by aeronautic engineers, is the process whereby the output of an engine at sea level is maintained at altitudes. Forced induction, by means of a rotary blower, has however been tried on automobile engines. Only one maker, Mercédes, has so far incorporated this feature in the standard design. This practice has much to be said for it, as a small engine may be made to give a large output without running abnormally fast, or resorting to special fuel.

It would be interesting to consider the application of superchargers to aero engines with this idea of obtaining large outputs from small engines. Given good design, an actual increase in horse-power for a given weight would result.

In seaplanes it would be possible in some cases to employ smaller engines running non-supercharged at all times other than at great heights top speed and to get over the hump speed when taking off. The above remark applies to commercial rather than war seaplanes.

It is now necessary to consider the phenomena which influence the behaviour of the engine as the altitude increases, and secondly, methods whereby the ground level conditions may be maintained. The chief of these are :—

1. *Reduction in pressure.*—This has the effect of lowering the compression and mean effective pressure with consequent diminution in output.

The pressure on the pistons bears a constant ratio to the compression pressure and to the density.

Since for a given engine speed the horse-power varies as the mean effective piston pressure, then the output varies directly as the air density, other things being equal, or

$$H = H_1 (\rho/\rho_1)$$

H = H.P. at air density ρ
H_1 = H.P. at air density ρ_1

2. *Reduction in temperature.*—The effect of this is to cause a charge of greater density to enter the cylinder on the suction stroke, although for a given altitude this by no means compensates for the corresponding reduction in pressure.

The relation between altitude and temperature is given by the empirical formula

$$\theta = 15 - .0065\, Z$$

θ = temperature in ° Centigrade at an altitude of Z metres.

This formula is accurate for practical purposes up to an altitude of 11,000 metres.

The reduction in pressure is similarly given as

$$\rho_1 = \rho_0 \left[\frac{288 - .0065\, Z}{288} \right]^{5.255}$$

where ρ_1 = the pressure at altitude Z metres,

ρ_0 = the pressure at sea level.

At only 1,525 metres (5,000ft.) the air density is reduced to 86 per cent. of the sea level value, giving a corresponding decrease in engine output. This is partly compensated for by an increase of 3 per cent. due to a reduction in temperature, giving a total horse-power reduction of 11 per cent. It is worth replacing this 11 per cent. in output, even at the cost of the weight and complication of a supercharging device.

Among the methods which may be employed are the following :—

1. The engine is fed with oxygen at altitudes or a special fuel may be employed which will not detonate at a high compression ratio at ground level Both these call for the provision and carriage of special substances which cannot everywhere be obtained. These may therefore be dismissed as impracticable.

2. A high compression engine may be run throttled on the ground and gradually opened out as the aircraft climbs, thus obtaining a greater expansion ratio at altitudes with corresponding increased thermal efficiency and output. The extent to which this process can be carried is limited. An engine having a compression ratio of 7 : 1 was run throttled on the ground with petrol, detonating normally at a compression ratio of 4.85 : 1. In this case the brake mean effective pressure did not exceed 70 lbs. per square inch, which would not be sufficient to allow the aeroplane to leave the ground at all.

3. A high compression engine may be run at or near the sea level with a mixture of combustible gas, air, and cooled exhaust gases. This system has been used on large gas engines, but has not, so far as I am aware, been applied to aircraft engines.

4. A variable compression ratio might be employed and gradually increased as the air density decreases. To put this idea into practice would necessarily call for serious mechanical complication, however.

5. Holding the inlet valve open during a portion of the compression stroke has been proposed, thereby obtaining a large expansion ratio, while the compression temperature and pressure are reduced. This does not call for the solution of so serious a mechanical problem as does No. 4. A drawback of this arrangement is the sudden reversals of gas flow in the induction system, thus interfering with proper carburation.

All the above systems are probably better suited for maintaining the output at altitudes than for obtaining, as well, a large output at sea level, for a small volumetric capacity of the engine, which would seem so desirable.

This can be and has been done by forcing air under pressure through the carburettor and into the engine cylinder by means of a fan or other blower. Rotary and piston blowers are at an obvious disadvantage as compared with a centrifugal fan.

The Fan

This is usually a single stage centrifugal fan running at 20,000 to 30,000 r.p.m. The efficiency of the apparatus cannot be much higher than 55 to 60 per cent. I cannot obtain data as would enable me to compare the relative efficiencies of simple *versus* multi-stage blowers, but whilst single-stage centrifugal water pumps attain to an efficiency of 75 per cent. against heads of up to 100ft. with multi-stage turbo-pumps, heads of 1,500ft. are overcome with an efficiency of 80 per cent. It must also be remembered that the heat generated

in the compression of the air has an adverse effect on the volumetric efficiency of the engine. This heat must therefore be removed by means of an air radiator. To dispose of a large quantity of low temperature heat is always troublesome. It would seem beneficial to employ a multi-stage compressor delivering air at a higher pressure and temperature, cool it in a smaller radiator, subsequently passing through a pressure-reducing device to the carburettor. By reason of the greater temperature difference between the air within and without the radiator, a smaller surface for the same duty should be possible with consequent reduction in weight and head resistance. This should go far towards compensating for a possibly higher temperature on the carburettor side of the radiator than in the case of the standard one with a single-stage blower. Against this idea is the more complicated compressor requiring more power to drive it, together with losses in the reducing apparatus.

Methods of Driving Fan

1. A separate engine has been employed in some German aircraft. This arrangement is heavy and has no outstanding advantages for other than large power plants.

2. An exhaust-driven single-stage turbine is used to drive the compressor, as in the Ratian supercharger. The chief merit of this type is its ability to adjust its output automatically to the needs of the engine, in that as the pressure of the atmosphere into which the turbine exhausts decreases, the output of the blower increases to supply air at the necessary pressure to the engine. On the contrary, the turbine cannot operate at a sufficiently high speed or temperature for the best results. It therefore follows that much of the work done by the turbo-compressor is represented as back pressure on the pistons allowing hot residual gases to remain in the cylinders at the end of the exhaust stroke at a pressure greater than that of the fresh charge about to enter. A further drawback is the conduction of heat from turbine wheel to the fan, thus heating the air, which has afterwards to be cooled.

3. The compressor may be driven by gearing from the main engine. This arrangement has been tried out in Germany. Difficulties have been encountered with the gears in that, by its flywheel effect, the compressor rotor tends to rotate at uniform angular velocity, while the crankshaft is subject to cyclical oscillations with consequent wear on the gears. This will, no doubt, be overcome in the future by means of adequate flexible couplings and damping devices. This type has the advantage that there is no back pressure on the pistons. The gearing being of fixed ratio, the compressor cannot always rotate at such speed as will best cater for the requirements of the engine. It would appear to our advantage to develop some form of variable-speed mechanical or electrical transmission between engine and compressor. With the aid of such a gear the chief merit of the exhaust turbine-driven apparatus would be shared by this system. The former would be more satisfactory in small plants, whilst the weight of the latter may put it out of court.

A supercharger of this type was built and tried by Brown Boveri at Mannhiem in 1917. The compressor was of the multi-stage type driven by the engine through a torsional damping device. The speed of rotation was about 10,000 r.p.m., calling for very high-class material and workmanship in the construction of gears and rotor, all bearings being carried on rollers. The apparatus weighed 125 lbs., designed for a 260 h.p. engine, 25 h.p being required to drive it. An A.E.G. aeroplane fitted with this apparatus reached an altitude of 20,000ft. There was also a marked increase in the top speed of the machine. This combination of a multi-stage blower driven through a variable-speed gear from the main engine is, in my opinion, the most practicable of those which have been described, and has the greatest future before it, although this does not

mean to say that it is perfect, but rather that the system provides ample scope for improvement which can only come with time and labour, and that its peculiar difficulties are more likely to be overcome than are those peculiar to other types.

Conclusion

It is necessary to add that such a subject as the above cannot be covered in a paper such as this. A volume might be written on it. The paper has been prepared in somewhat of a hurry, and doubtless many interesting and important points remain untouched. I am also indebted to the works of Messrs. Judge, Ricardo and Gibson for some of the above information.

RÉSUMÉ OF TECHNICAL INFORMATION

JUNE—JULY, 1926

Compiled by the Directorate of Technical Development (R.T.P.), Adastral House, Kingsway, London, W.C.2.

AIRCRAFT

France

Endurance Test with a De Monge 7-5.

Les Ailes, 3rd June, 1926, No. 259 (1826).

Captain Cousin is to attempt an endurance test with a De Monge 7-5 on the circuit Paris-Rouen-Paris.

This machine, which has completed its tests at the S.T.Ae., weighs 748 kg. with its pilot, 50 litres of petrol and 30 kg. of instruments.

Fitted with two 35 h.p. Bugatti engines and weighing 3 kg. per h.p., the wing loading is 38 kg./sq. m. and the power loading 11 kg./h.p.

Speed near the ground is 153.3 km./hr. and it climbs to 6,560ft. in 24 minutes.

The load factor is 13.

The wing is of the cantilever type, is in three sections, and can be very quickly dismantled.

Germany

New Junkers Aircraft.

Berlingske Tidende. 5.8.26 (2826).

Dr. Karje, one of the chief engineers at the Junkers Works, Dessau, stated in an interview at Copenhagen that the Junkers factory has just completed an entirely new three-engined aeroplane, the G.31, which has accommodation for eighteen passengers.

This aircraft constitutes a further step towards a giant aeroplane which Professor Junkers has designed, a model of which may be seen at his laboratory. This giant aeroplane is to have accommodation for 100 passengers and will constitute a formidable rival to the railways. The present difficulty is to find the money to build, but as soon as this is forthcoming construction of a giant Junkers aeroplane will begin.

Italy

The Breda 10.

La Gazzetta dell'Aviazione. 29.7.26 (3826).

The Breda 10 is a biplane for training fighter pilots. It is of mixed wood and steel construction and very easy and economical to maintain. It is built either for instruction purposes when it is fitted with disconnectable dual control, or as a single-seater fighter training machine. It is suitable for training pilots in stunting owing to its great strength. The characteristics are as follows:—Engine, 250 h.p. Isotta Fraschini; span, 8.4 m. (27ft. 6in.); chord (mean), 1.1 m. (3ft. 7in.); wing area, 17.7 sq. m. (190.5 sq. ft.); overall height, 3 m. (9ft. 10in.);

width of fuselage, 0.9 m. (3ft.); useful load, 300 kg. (661 lbs.); total loaded weight, 1,050 kg. (2,314 lbs.); endurance, 2½ hours; load factor, 12; maximum speed, 225 km. per hour (139 miles per hour); minimum speed, 80 km. per hour (49 miles per hour); ceiling, 6,000 m. (19,680ft.). The aircraft is also fitted with a 220 h.p. Spa 6-A engine.

U.S.A.

The Travel-Air Mail or Passenger Plane.

Aviation. 12.7.26 (4826).

The new Travel-Air Cabin plane is a development of the well-known standard Travel-Air three-seater machine. The plane retains all the excellent qualities of the open cockpit Travel-Air, but seats four passengers in a comfortable closed cabin which is entered by raising the side windows and roof.

The machine is also intended to be used as a mail plane. When used for this purpose the space available for express matter is 55 cub. ft. when the machine is fitted with an Hispano Suiza engine. When equipped with a Wright Whirlwind radial engine the available space is 60 cub. ft.

In the absence of the official flight tests the following data has been supplied by the manufacturers :—

With 180 h.p. Hispano Suiza engine and 700 lbs. pay load—
Maximum speed, 110 m.p.h.; landing speed, 40 m.p.h.; climb to 1,000ft., 1 min. 45 secs.

With 200 h.p. Wright Whirlwind engine and 800 lbs. pay load—
Maximum speed, 120 m.p.h.; landing speed, 40 m.p.h.; climb to 1,000ft., 1 min. 30 secs.

Kinner Monoplane.

Aviation. 12.7.26 (5826).

The Kinner monoplane, the successful performance of which under fifteen flight tests has decided its producers, the Kinner Airplane and Motor Corps of Glendale, Calif., to begin manufacture, is equipped with a Lawrence three-cylinder engine, and is of the enclosed coupe type. Future planes will be equipped with the 6A-3 h.p. Anzani engine, and if the open cockpit is preferred, it will be installed. The coupe has two windows directly over the pilot's seat. This plane is now of single control, the passenger sitting a little to the rear and about 4in. lower than the pilot. Future machines will be equipped with dual control, making it an ideal training plane.

The fuselage is of plywood construction, with bulkheads in the forward part and gusset plates in the rear sections. The tail group is of steel, with tube covered with fabric and doped. The wings are conventional with ribs of plywood and spruce capstrings. Box spars are built up with spruce capstrings and plywood sides.

The general details, together with the manufacturer's performance figures, these being given in the absence of official tests, are as follows :—Span, 31ft. 6in.; length, 21ft.; height, 7ft.; chord, 6ft.; speed, 85 m.p.h.; landing, 30 m.p.h.; climb, 13,000ft.; first min., 1,000ft.; weight, 700 lbs.; factor of safety, 5.

The Laird Commercial.

Aviation. 26.7.26 (6826).

The Laird Commercial plane is a three-seater tractor biplane of medium power, designed for general commercial flying, primary training, or feeder-line transport service. The plane is powered with either the 200 h.p. Wright Whirlwind, the 160 h.p. Curtiss C6, or the 90 h.p. Curtiss OX5 engine.

It is evident that particular attention has been paid to primary commercial requisites such as safety, economy, accessibility, and ease of maintenance. Strength factors conform to service requirements and a load factor of eight has been carried throughout the structure.

The general details of the Laird Commercial plane are given therewith for the three engine installations. In the absence of official flight-tests, the manufacturer's figures of performance are given :—

With Curtiss CX5 engine.—Span (both wings), 33ft. ; cord (both wings), 5ft. ; total wing area, including ailerons, 300 sq. ft. ; length overall, 23ft. 6in. ; height, 9ft. 3in. ; wheel tread, 60in. ; weight (light), 1,350 lbs. ; pay load, 300 lbs. ; wing load, 6-8 lbs. per sq. ft. ; capacity of fuel tank, 60 gallons ; cubic capacity of cockpit, 20 cub. ft. ; maximum speed, 95 m.p.h. ; cruising speed, 80-85 m.p.h. ; landing speed, 40 m.p.h. ; climb (first minute), 600ft. ; climb in ten minutes, 5,000ft. ; ceiling, 16,000ft. ; take-off distance, 250ft. ; cruising range, 600 miles ; cruising endurance, 6½ hours.

With Curtiss C6 engine.—Weight (light), 1,500 lbs. ; pay load, 500 lbs. ; capacity of fuel tank, 75 gallons ; cubic capacity of cockpit, 25 cub. ft. ; maximum speed, 120 m.p.h. ; cruising speed, 100 m.p.h. ; landing speed, 45 m.p.h. ; climb (first minute), 1,000ft. ; climb in ten minutes, 7,500ft. ; ceiling, 18,000ft. ; take-off distance, 200ft. ; cruising range, 600 miles ; cruising endurance, 6 hours.

With Wright Whirlwind engine.—Weight (light), 1,550 lbs. ; pay load, 800 lbs. ; capacity of fuel tank, 80 gallons ; cubic capacity of cockpit, 20 cub. ft. ; maximum speed, 130 m.p.h. ; cruising speed, 110 m.p.h. ; landing speed, 40 m.p.h. ; climb (first minute), 1,350ft. ; climb in ten minutes, 10,000ft. ; take-off distance, 150ft. ; cruising range, 600 miles ; cruising endurance, 6 hours.

POWER UNITS

France

Diesel Engine for Aircraft.

Les Ailes. 1.4.26, No. 250 (7826).

A celebrated French engineer has been studying the problem of the Diesel engine for aircraft and made exhaustive experiments.

Interesting results are expected shortly. Dr. Frey has designed a Diesel engine for motor-bicycles, which is a single-cylinder engine with bore 80 mm. and stroke 90 mm.

It runs on gas oil and develops 6 h.p. at 2,400 r.p.m. ; whilst running light it attains 4,000 r.p.m.

The fuel consumption is 250 gr. per h.p. hour.

The adaptation of such an engine to a light plane will be awaited with interest.

Italy

Remarkable Flight Test of New 500 h.p. Asso Engine.

La Gazzetta dell'Aviazione. 22.7.26 (8826).

The new Asso engine built by Isotta Fraschini has just carried out a 150 hours' flight test at Sesto Calende. The engine was mounted on an S.16 ter seaplane. Three well-known pilots, Lieut. Bacula and Sub-Lieuts. Cagna and Valdimiro, piloted the aircraft during the test. After two six-hour tests carried out at the request of the members of the Commission, and climb and load tests (to 5,400 metres) (17,720ft.) with 800 kg. (1,764 lbs.) of load and to 5,100 metres (16,730ft.) with 1,000 kg. (2,205 lbs.) (of load), the final test began. The seaplane flew every day for a fortnight from 7 a.m. to 1 p.m. and from 2 to 7 p.m. (ten

hours). A Military Commission of four members accompanied the pilots during the test.

The mean speed was 180 km./hr. (112 m.p.h.), so that 27,000 km. (16,780 miles) was covered in the course of the fortnight. The longest flight test previous to this either in Italy or abroad seems to have been 100 hours.

MISCELLANEOUS

U.S.A.

Propeller Studied in High-speed Tunnel.

Aviation. 12.7.26 (9826).

An air stream having a velocity of 700 m.p.h. or more has recently been used by the Bureau of Standards in work on airplane propeller design for the National Advisory Committee for Aeronautics. The tips of airplane propellers move through the air at speeds of 600 to 700 m.p.h., and in order to study the efficiency of the blade in detail, measurements must be made at the speed at which the blade moves when in use.

Experiments of this kind are made with a stationary blade in a moving air stream, because the forces acting on the blade and the pressure distribution over its surface are more readily measured in this way.

A group of large compressors at Edgewood Arsenal, used during the war for refrigerating mustard gas shells, was utilised to supply the high-speed air stream.

Among other points, the experiments have shown that thin metal propellers now coming into use are more efficient at very high speeds than wooden propellers, in which thicker sections must be used to secure sufficient strength.

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REVIEWS

Ergebnisse der Aerodynamischen Versuchsanstalt zu Gottingen. I. and II.
(R. Oldenbourg, Berlin. 6.50 M.)

A description of the wind tunnels at Prandtl's laboratory and the work carried out therein since 1920. The tunnels are continuous, the air being driven round a rectangular track, the experimental portions having cross-sections of 4 sq. m. in the large tunnel and 2 sq. m. in the smaller one. They are driven by motors of 225 kw. and 30 kw. respectively. Of interest is the arrangement for producing rays of smoke in the small channel, in connection with the examination of the flow of air around models. Most of the tests described are routine examinations of the resistance of a number of aerofoil shapes; also of aerofoils whose profile is divided into a number of non-contiguous parts. The second volume also contains a theoretical paper on the induced resistance of the multiplane.

Leichtflugzeugbau
By G. Lackmann. (R. Oldenbourg, Berlin. 13 M.)

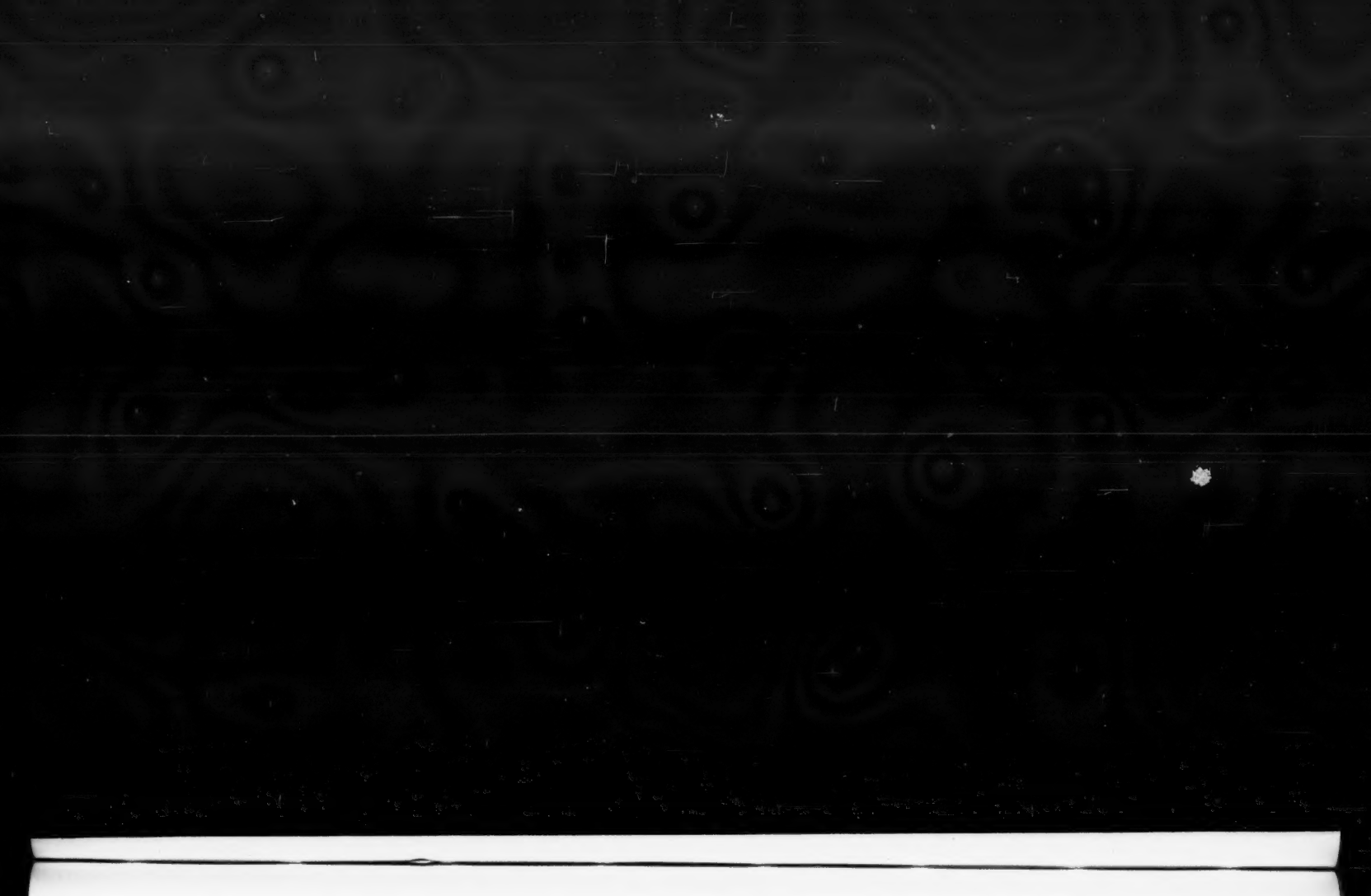
One gathers from this book that the light plane in Germany has, up to the present, been neglected in favour of the glider. Of the section devoted to light plane types in various countries, the German industry occupies quite a small place, the major portion being given to the machines in the first Lympne trials. The author ascribes the slowness of development of the light plane to the unsuitable motors—of high compression and revolutions—offered by the German motor firms. A structure is built as light as possible, and in it the lightest possible (and necessarily weak) motor is placed. The author thinks that the direction of progress lies in building a plane requiring normally, say, 15 h.p., and building into it a motor capable of 35 to 40 h.p. The next section of the book gives the theory of resistance and of the airscrew, but does not seem to have any especial reference to the light machine, and might have been omitted. The section dealing with actual construction is—in spite of the title of the book—quite small, and consists of abstracts and photographs from *Flight*, descriptive of the building of small English machines. The book gives a useful survey of the subject, but most of the material is available to English readers in our native journals.

***Jahrbücher der Wissenschaftlichen Gesellschaft für Luftfahrt,* 1924, 1925**
(R. Oldenbourg, Berlin. 14 M. each.)

Apart from reports of the routine business of the Society's meetings, these two books contain a number of interesting technical papers, of which space will permit only the citation of a few. Rohrbach deals with the construction and performance of a large seaplane having the wings set in V position at an angle of 6° to the horizontal; a system shown to have advantages in ease of steering. Ackeret describes recent model research at Göttingen, including arrangements for rapidly rotating a cylinder for experiments on the Magnus effect, and a small electric motor for driving the airscrew of a model plane, allowing wind channel tests to be made with the airscrew running.

Behm has carried out tests with his " echo-sounder " on airships and aeroplanes. This provides a novel and ingenious method for finding the height of

an aircraft. On one side a cartridge is exploded, starting a sound wave which travels out to the nearest point of the earth's surface, is there reflected, and the echo received by a microphone placed on the opposite side of the aircraft. From the length of time of traverse and return of the sound the height is directly calculated. The firing of the cartridge starts the movement of an indicator over a dial until the reception of the echo stops it. The dial is graduated directly in metres. Difficulties are encountered at small heights, *i.e.*, when an accurate measurement is most needed, but Behm has overcome these and claims to measure heights down to about 2 metres with an accuracy of 10 cms.!

Photographs in the form of cinematograph films are shown of the airflow past rotating cylinders, showing the preponderance of vortices on one side of the wake (by Tietjens), and of the longitudinal oscillations of a model glider (by Scheubel). Finally, Madelung describes the competition for the Otto Lilienthal prize. The following list of measurements which were made by special instruments and recorders at each flight in the competition exemplifies German thoroughness:—(1) Plane surface; (2) motor performance; (3) tare weight; (4) load; (5) fuel consumption and heat production; (6) weather; (7) height; (8) angle of ascent; (9) maximum, minimum and average speed; (10) space required for taking off and landing. Daimler L20 scored the most points in this meticulous test.

For details of these and other interesting papers, the original should be consulted.